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MIPR NUMBER 96MM6675/96MM6674

TITLE: Savage Medical Resupply Projectile

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Army Research Laboratory
Aberdeen Proving Ground, MD 21005

REPORT DATE: October 1996

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for public release;
distribution unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1996	Final (14 Mar 96 - 30 Sep 96)

4. TITLE AND SUBTITLE
Savage Medical Resupply Projectile

5. FUNDING NUMBERS
96MM6674/96MM6675

6. AUTHOR(S) MAJ Charles E. Dean, John W. Molnar, Daniel J. Weber, William P. D'Amico, Fred Brandon, Bradford Davis, Michael S. L. Hollis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Army Armament Munitions
Aberdeen Proving Ground, MD 21010-5423

Army Research Laboratory
Aberdeen Proving Ground, MD 21005

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commander
U.S. Army Medical Research and Materiel Command
Fort Detrick, Frederick, Maryland 21702-5012

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200*

The research described within this document supports a developmental effort to design and test 155mm artillery shells for rapidly and accurately delivering replacement medical fluids to ground units during combat. The scope of this particular work package was to (1) demonstrate that commercially available intravenous fluid bags could withstand the high launch forces experienced by 155mm artillery projectiles when fired, and (2) demonstrate through actual cannon firings that these medical resupply projectiles exhibit stable flight. The results show that proper packaging will permit off-the-shelf intravenous fluid bags to survive cannon launch type forces. Additionally, laboratory experimentation has shown that the projectiles, when spun up to transit conditions, demonstrate dynamic stability. Gun launch; however, has shown to date that these projectiles become unstable during actual flight. Recommendations are proposed to further study the flight instabilities experienced to render these projectiles fully stable.

14. SUBJECT TERMS
Non-rigid payloads, liquid-fill instabilities, resupply projectile, logistics resupply, Savage, medical projectile

15. NUMBER OF PAGES
55

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

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N/A In conducting research utilizing recombinant DNA technology, the investigator(s) adhered to current guidelines promulgated by the National Institutes of Health.

N/A In the conduct of research utilizing recombinant DNA, the investigator(s) adhered to the NIH Guidelines for Research Involving Recombinant DNA Molecules.

N/A In the conduct of research involving hazardous organisms, the investigator(s) adhered to the CDC-NIH Guide for Biosafety in Microbiological and Biomedical Laboratories.

Charles E. Dean 27 Jan 97
PI - Signature Date

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ACKNOWLEDGMENTS

The authors would like to thank COL William P. Wiesmann, MC of the U.S. Army Medical Research and Material Command for his outstanding support of the medical resupply program, and for providing the necessary funds for this investigation. In addition, the authors would like to thank Mssrs Eugene Ferguson, David Vasquez, and Eric Irwin for their work in acquiring data from the yawsonde sensors. The authors would also like to thank the members of Transonic Range for making the test a reality. Mssrs. James Garner, Vural Oskay, John Heath, Barry Hudler, Robert Keppinger, Kenneth Willian, James Foley. These gentlemen overcame adverse weather conditions and strict testing windows to perform the experiment.

SAVAGE MEDICAL RESUPPLY PROJECTILE

1. INTRODUCTION

An investigation into the feasibility of delivering medical supplies via a 155mm artillery projectile system, was conducted at the Edgewood Research, Development and Engineering Center (ERDEC) and the Army Research Laboratory (ARL). The Savage Resupply System was designed to provide combat units with critical supplies necessary for their survival when cutoff from normal logistic lines. The Army Medical Corps quickly identified intravenous (IV) fluids as a high priority and crucial resupply item. The design of the Medical Resupply Projectile (MRP) was initiated to address the IV resupply needs of the Medical Corps. A three phase feasibility study was conducted to determine if IV bags could withstand the harsh launch environment of a 155mm projectile, and once in flight, determine if the IV bags would induce a liquid payload flight instability. Initial efforts have focused on resuppling intravenous fluids and small arm ammunition, but the system can easily be expanded to include many other supply items such as: batteries, food, etc.

In a parallel effort, Armament Research, Development and Engineering Center (ARDEC) was developing a small arms ammunition resupply subcanister as well as the overall Savage resupply module and parachute recovery system. Cooperative Research and Development Agreements (CRDA) were established with several companies to expedite and assist with the development of the necessary canister hardware and parachutes needed to demonstrate the feasibility of the system.

2. BACKGROUND AND HISTORICAL NEED

Countless historical examples demonstrate both the need for emergency resupply and the detrimental results when crucial materials do not reach the intended units in time.[1] Despite the advent of new technologies, our forces continue to fight without a system that can deliver critical supplies quickly, accurately, and safely without being impeded by enemy forces, terrain, or weather.

The lack of critical supplies in combat leads to several consequences. When units begin to experience shortages in ammunition they frequently break off engagements, overly restrict their weapon fires, surrender, or, ultimately, die with empty rifles. When soldiers die of wounds in battle, many of these combatants perish from excessive loss of bodily fluids. Combat statistics show that of these soldiers, most of them not only die within the first hour of injury, but the majority succumb to their wounds within the first fifteen minutes.

The primary goal of Combat Trauma Medicine is to reach the wounded soldier within the first fifteen minutes of wounding with sufficient resuscitation capability. Combat medics and ground soldiers carry intravenous fluid bags into battle. As soldiers get wounded, rapid resuscitation by fluid replacement is crucial to saving their lives and

the on-hand supplies of intravenous fluids are rapidly consumed. Unfortunately, replacement intravenous fluid bags become very difficult to acquire.

From the beginning of the Second World War to the present, major advances have been made in developing new vehicles for permitting humans to transport and deliver combat logistics. Among these technologies are aircraft that deliver numerous cargo bundles by parachute, helicopters that fly directly to embattled units, and more versatile wheeled vehicles that can better negotiate rough terrain. These "conventional" systems all have great strengths but they are also all restricted by weather, terrain, and enemy action. Frequently, the use of these technologies has led to losing valuable time while preparing and executing the resupply missions, poor weather delaying or hampering the operation, loads being delivered to the wrong locations, and humans and their vehicles being destroyed.

3. HOW SAVAGE WORKS

The flight sequence of the Savage resupply system is illustrated in Fig. 1[1]. When

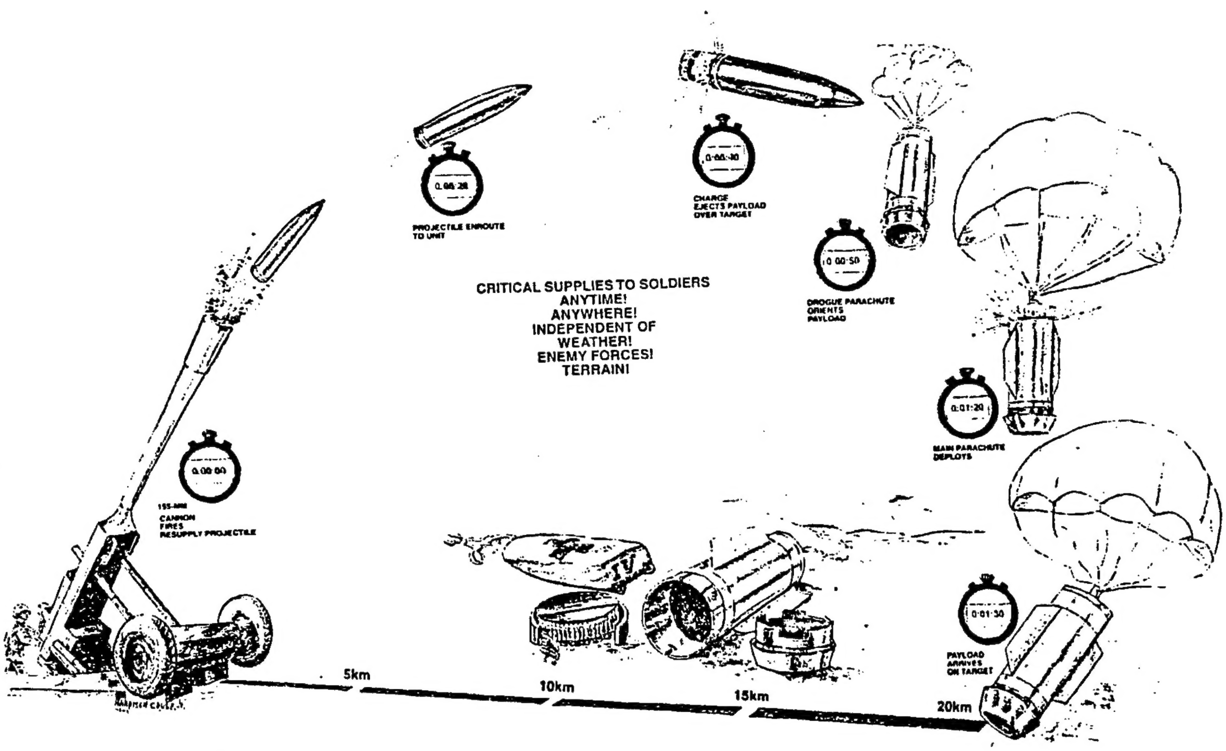


Figure 1: Conception of Combat Resupply Via 155mm Artillery

a unit requests Savage resupply, each shell will be fired over its position. High above the unit's location the main projectile fuze will function and initiate the expulsion charge within the nose of the shell and eject the resupply canister from the base end of the projectile. The now empty shell body will continue along its original trajectory and land

at least one kilometer away from the requesting unit. As soon as the resupply canister departs the shell body, a drogue parachute will deploy to slow and despin the canister. As the resupply canister continues to fly toward its target, a timing device will cause the main parachute to deploy at a low altitude. Low level opening of the main parachute is desired to maximize the accuracy of delivery by minimizing undesired drift. As the main parachute deploys, a second timer will activate to initiate the canopy release assembly one minute later. The main parachute will slow the descent velocity of the canister and will provide early warning to ground forces of the canister's arrival. After the load lands, the canopy release assembly will sever the suspension lines from the canister to permit the canister to drop to the ground should its parachute become entangled in trees, telephone poles, etc. Activation of the canopy release will be contained within the assembly and will not pose a safety hazard to anyone holding the device. Figure 2 shows the cut away of the Savage projectile.

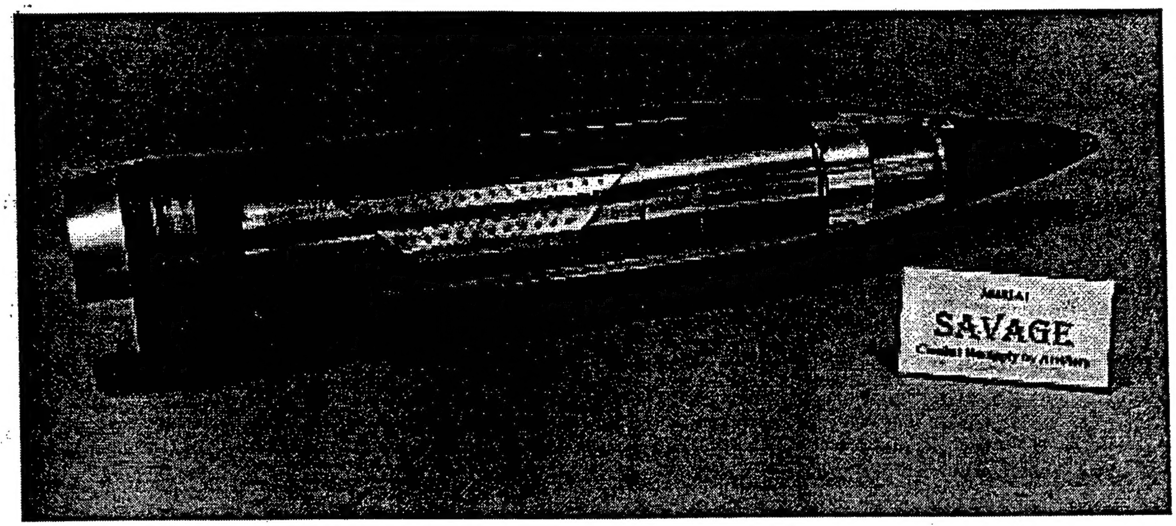


Figure 2: Cutaway of the Savage Projectile Showing the Resupply Canister

The Savage program intends to use existing M483A1 shell bodies. The M483A1 projectiles are currently designed to deliver dual purpose improved conventional munitions. These rounds presently exist in the inventory, and close to a million of them are schedule for destruction over the next few years. By using these rounds in the Savage program, a great cost and time savings can be realized since a new delivery projectile will not have to be designed, tested and produced.

4. MRP FEASIBILITY STUDY

4.1 Overview of Non-Rigid Payload Instabilities

In order to appreciate the problems associated with liquid-filled shells, a basic understanding of projectile flight motion is needed. In flight, a projectile is stabilized gyroscopically, much the same way a toy top is stable while spinning on a table. The spin along with the mass properties of the projectile generate a stabilizing gyroscopic moment which if large enough, offsets the destabilizing aerodynamic effects acting on the exterior of the projectile. All projectiles as they fly through the air exhibit a complex cyclic motion. Not only is the projectile spinning about its long axis, but it is also nutating (also called fast precession or fast mode) and precessing (also called slow precession or slow mode). Figure 3 illustrates this complex epicyclic motion of a spin

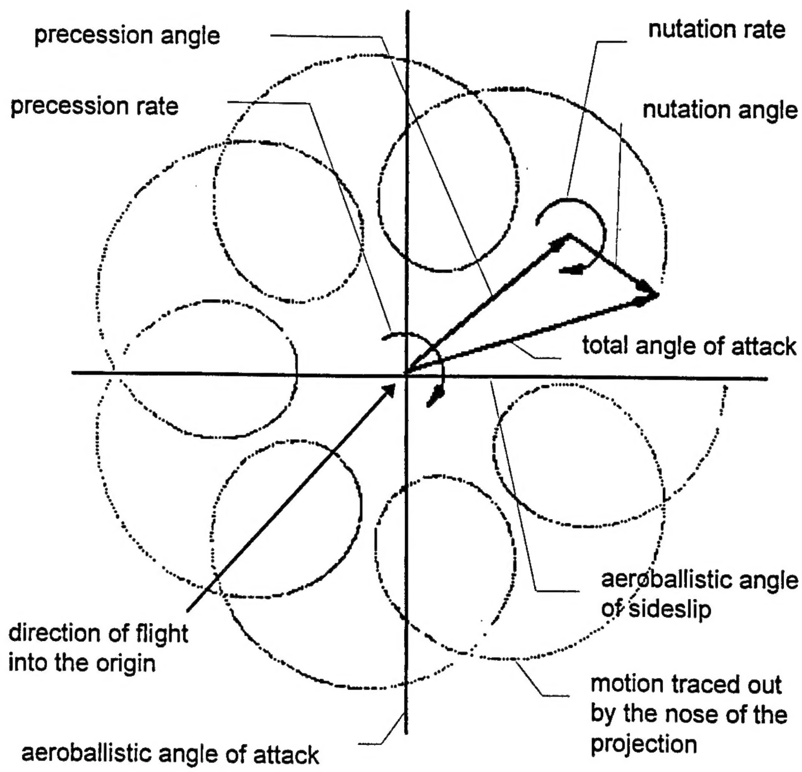


Figure 3: Epicyclic Motion of Spin Stabilized Projectile

stabilized projectile. The flight path of the projectile is through the origin of x-y plot with the projectile orbiting the origin as indicated. The precession motion of the projectile is represented by the large circle motion and has the slowest frequency, approximately two orders of magnitude below the projectile's spin rate. The small loops denote the nutation motion of the projectile which has a frequency approximately one order of magnitude less than the spin rate. The nutation of the projectile is sometimes also referred to as "coning" or "wobbling". For a spin stabilized projectile, all three rotational motions have the same

direction. Generally speaking, for a stable projectile, the precession and nutation motion is damped, or at the very least does not grow which is referred to as a limit cycle. Usually the precession motion is damped, while under certain conditions, e.g., some liquid payloads, the nutational motion can diverge. It is this motion of the projectile, spin and nutation, in combination with the payload canister geometry and liquid properties that can lead to non-rigid payload instabilities.

With IV bags being chosen as the most critical medical resupply item, the possibility of a non-rigid payload instability was a major concern. It is important to note that non-rigid payload instabilities are not limited to just "liquid-fills".[2, 3] Many different types of non-rigid payloads (internal mechanical linkages, loose small parts, etc.) can cause instabilities that resemble those produced by liquid-fills. In addition, the two types of liquid instabilities discussed in this report are due to complex flow fields established within the liquid payload which are induced by the projectile's flight motion. These liquid induced instabilities should not be confused with instabilities caused by the sloshing motion of the liquid payload due to a less then 100% fill. Sloshing type instabilities are a more common stability problem for satellites, and typically do not cause flight problems for spin stabilized projectiles. With respect to less than 100% fills, studies have shown that ullages (voids in the payload compartment) from 50 to 100% can produce the same level of liquid destabilizing moment in a projectile.[4] For this study, the MRP payload compartment was between 90 and 100% full, depending on what IV bags were being used.

Typically, for a right circular, cylindrical payload canister there exists two types of liquid-fill instabilities which are both functions of the payload's viscosity, the canister's geometry and the projectiles flight characteristics. Figure 4 graphically depicts, in three dimensions, the entire range of liquid instabilities and their associated conditions for both low and high viscosity fluids. The first type of liquid induced instability was identified by Stewartson[5]. He was able to determine that a low viscosity fluid, such as water, could produce a resonance instability which occurred between inertia waves in the liquid payload and the projectiles nutational (coning) frequency. A resonance instability is very sensitive to the payload canister's geometry. Typically, a Stewartson's instability can be avoided by a small change in the payload canister's geometry (i.e., varying the length to diameter ratio of the canister). The second type of instability, named a viscous instability, is due to the viscous properties of high viscosity fluids, such as corn syrup or tar. Simple geometry changes have little affect on this type of instability. Thus a viscous instability is difficult to avoid and/or correct.

The internal configuration such as baffles,[6,7] interior surface roughness[8], etc., of the payload canister can also cause unexpected problems. Due to the flexibility of the IV bags and their associated packaging requirements, a baffle/support was required for the MRP. This baffle system also raised stability concerns based on the results from a limited number of experimental[6] and flight test[7] programs which were conducted in 1992-1993 to study the effects of baffles on the stability of liquid payload projectiles. The hypothesis supporting these studies was that the baffles would improve stability. In some

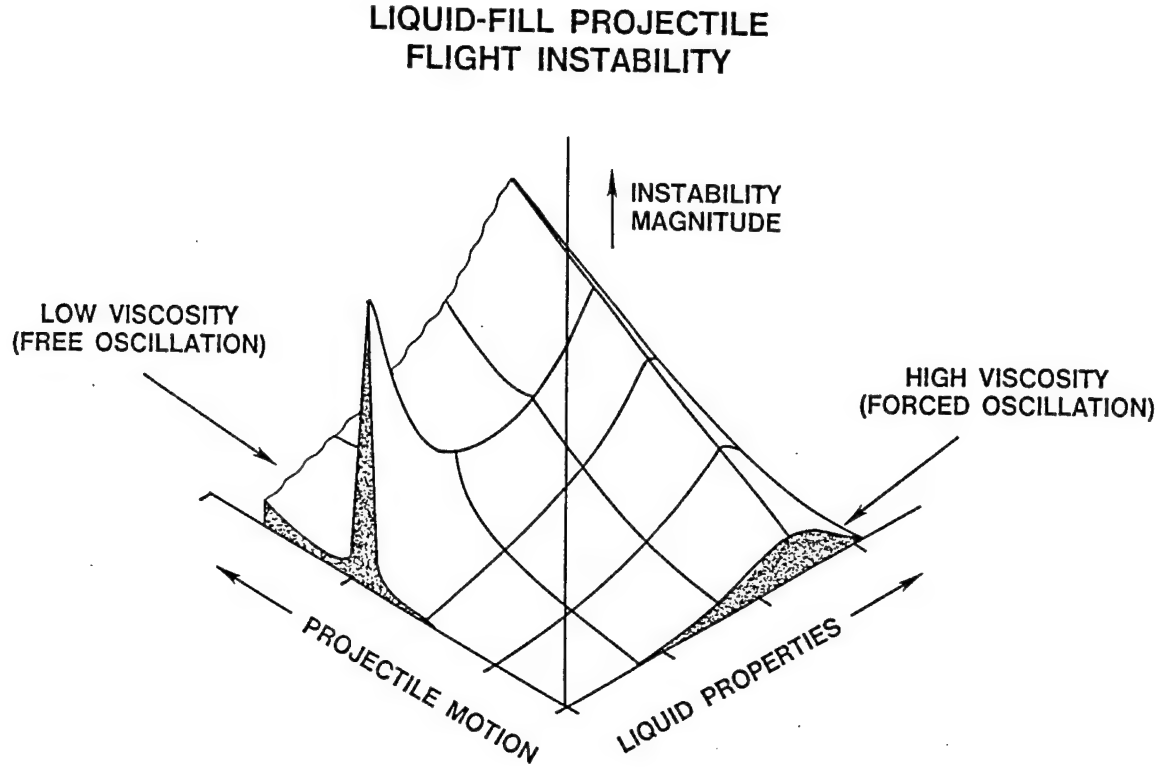


Figure 4: Three Dimensional Representation of Liquid-Fill Induced Instabilities

cases, especially for the high viscosity fluids the baffles helped, but for low viscosity fluids, baffles could cause a normally stable liquid payload to become unstable. From a physical point of view, what is believed to be happening is that the baffle artificially raises the viscosity of the fluid. A low viscosity fluid in a baffled payload canister appears to be a more viscous fluid, and thus susceptible to a viscous type flight instability. High viscosity fluids in a baffled container behave more like a solid with an associated reduction in destabilizing moment. The importance of performing a stability analysis on new non-rigid payload configurations cannot be overemphasized.

4.2 Methods for Determining Non-Rigid Payload Stability Problems

There are three major approaches to determining if a non-rigid payload might cause a projectile stability problem. These approaches include: laboratory test fixture experiments, analytical and computational methods which model the projectile/payload system, and projectile flight tests. Each method has its limitations and assumptions, but when taken together, the combined approach provides a solid stability analysis for a variety of configurations and payloads. Because of the complexity of the interior configuration of the MRP payload canister (i.e., baffles and IV bags), it was beyond the scope of this study to include a computational or analytical analysis.

4.3 Three Phases of the Feasibility Study

The MRP feasibility study was divided into three phases. The first phase included the design of a payload canister for the IV bags that would maximized payload capacity using "off-the-shelf" IV bags, and assure survivability of the bags under launch set-back forces. In Phase 2 the canister configuration design from Phase 1 was tested under simulated flight conditions to evaluate its flight stability due to a liquid payload. Sufficient flexibility in the program's schedule allowed for minor alterations to the canister design and retesting on the spin fixture. The final phase of the feasibility study was a instrumented flight test conducted at the U.S. Army Aberdeen Proving Ground.

4.3.1 IV Bag Selection

IV bags are made of high strength clear plastic, come in a wide range of sizes (250 ml, 500 ml, 1 l, etc.), and contain a variety of intravenous medicines. Typically the shape of the IV bag is rectangular with a "pillow" like budge in the center of the bag. At one end of the long axis of the bag is a hanger, and at the other end are two ports for connecting the bag to separate IV tubing.

Because of the internal geometry of the M483A1 projectile body, optimal packaging of the IV bags within the projectile would required a complete bag redesign. Table 1 shows a comparison between different packaging configurations and the

Table 1: Ideal IV Bag Packaging Configurations

Configuration		Number of Bags		
		250 ml Bags	500 ml Bags	1000 ml Bag
	Disk	18	9	4
	Half Disk	18	8	4
	Third Disk	18	9	3
	Quarter Disk	12	8	4

corresponding ideal number of redesigned bags that would fit into the available space. For example, configuration 1 which has no longitudinal division of the payload canister, and would require the bags to be shaped like large hockey pucks, here eighteen 250 ml bags, or nine 500 ml bags or four 1 liter bags could ideally be packaged into the available payload volume. The three other configurations cut the payload canister longitudinally in half, thirds and quarters, respectively. The point of this exercise was not to propose a radical redesign of the IV bags, but instead to point out that for some configurations, minor design changes to an off-the-shelf bag could substantially increase the payload capacity of the projectile. For the half disk configuration, if the bag were modified to

better conform to half circle cross sectional shape, then eight 500 ml IV bags would ideally fit into the volume. Although this is the ideal case, accepting some loss for less than optimum packaging caused by the bag's hanger, connecting ports, etc., there should remain amble room for six 500 ml bags, as compared to only four standard off-the-shelf bags. Due to the limited scope of this study, a bag redesign was not attempted, and off-the-shelf IV bags were used.

Applying the ideal packaging configurations of Table 2, to the real constraints of off-the-shelf IV bags, the 500 ml bags were selected as the most optimum choice. This limited to four the number of bags that could be packed in the payload compartment. The Walter Reed Army Institute of Research suggested McGaw, Inc. as a possible supplier of IV bags. McGaw's is one of the largest supplier of IV bags to the health care industry. Walter Reed also suggested that Hespan and Lactated Ringer's would be two good candidates for battlefield resupply. IV bag and fluid properties for both solutions are listed in Table 2. A noticeable packaging shortcoming of the McGaw IV bags was that

Table 2: McGaw, Inc. IV Bag and Fluid Properties

	Lactated Ringer's	Hespan
Seal	Heat Sealed	Heat Sealed
Plastic Film	Same	Same
Air Filled Void, 500 ml bag	40-80 cc 8-16%	0-7 cc 0-1.4%
Relative Viscosity (cp)	1.01	4.42
Density (g/cc)	1.003	1.025
Specific Gravity	1.006	1.028

although flexible, they were significantly less pliable than other IV bags sold by other companies. Another characteristic of the IV bags that differed between manufacturer's was the amount of air inside the bag. McGaw bags tended to have a larger internal volume of air when compared to the same size and IV solution of other manufacturer's. There also were large differences in the amount of air in McGaw IV bags containing different solutions. For example, comparing a representative McGaw's 500 ml bag of Lactated Ringer's to the same size bag of McGaw's Hespan (see Table 2), the Lactated Ringer's contained approximately 6 to 11 times more air than did the Hespan bag. Comparing McGaw bags of a specific size and IV solution, the amount of air appeared to be constant between bags. The IV bag air volume was attributed to the different filling processes used during manufacturing of the various bags. Because concern was expressed that the air may cause the bags to rupture at the higher acceleration levels, acceleration tests were planned that involved removing the air from the bags via a syringe.

Although several limitations were noted with regard to the McGaw's IV bags, none were judged to be serious. Thus, based on their strong position in the health care industry, and the wide availability of their products, the McGaw bags were chosen for this study.

4.3.2 Phase 1 - Mechanical Design and Stress Analysis

4.3.2.1 MRP Payload Canister Design

The MRP payload canister design was created from an iterative process that determined an effective packaging configuration of IV bags into an artillery shell. The design centered around off-the-shelf IV bags. Shock table testing would first determine the survivability of the bags due to set-back acceleration loads and bag-to-bag interaction.

The initial packaging study was to place as many bags as possible into a hollow cylinder and determine the level of acceleration that could be achieved before a bag would rupture. The maximum acceleration that the bags were to survive was based on maximum artillery performance of approximately 10,000 g's, where one "g" is equivalent to the acceleration that an object experiences due to the force of gravity at sea level on the earth's surface, i.e., 9.81 m/s^2. Thus an object that is subjected to a 10,000 g acceleration would exert a force equal to 10,000 times its weight. The configurations, in which the bags were packed into the cylinder, focused on the orientation of the infusion ports. The orientation of the IV ports was a concern in studying the bag-to-bag interaction.

Being that the ARL/ERDEC design work on the MRP payload had begun before the ARDEC design of the Savage Canister had started, the inner diameter of the test cylinder was believed to be close to what the final MRP design would be. However, the allowable height was unknown, because the design of the parachute was not final. Therefore, the height of the test fixture was based on the shock table weight constraints. This allowed the cylinder of the test fixture to be of a length so as to allow enough volume for four 500 ml bags. The cylinder consisted of an aluminum 6065 tube stock that was threaded onto a mounting base, which in turn was mounted to the translating anvil of the shock table. The cylinder is sealed with a thin aluminum plate and a threaded sleeve which screws onto the cylinder and holds the plate. Figure 5 displays the initial test fixture mounted to the shock table.

The assembled cylinder dimensions were:

Outer Diameter:	133.3 mm
Inner Diameter:	120.4 mm
Assembled Internal Height:	277.0 mm
Internal Volume:	3153 cm^3

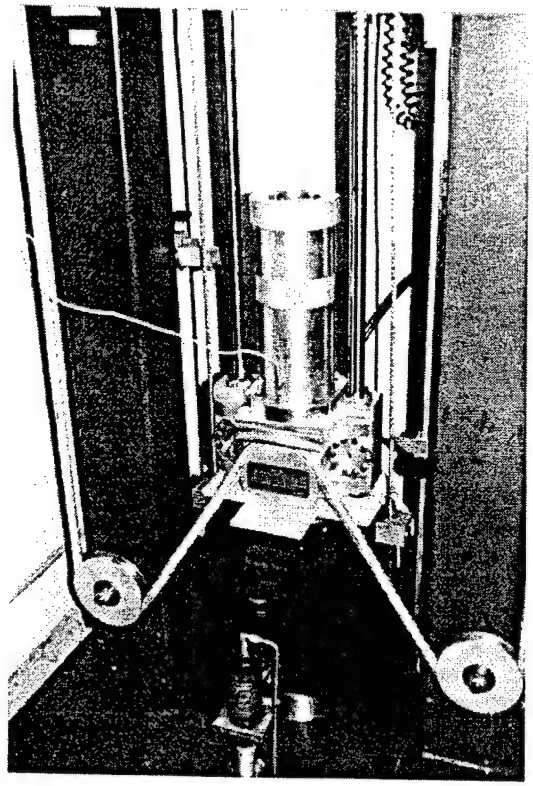


Figure 5: Test Canister Installed on Shock Table

In order to improve the IV bag's chance of surviving the projectile's set-back acceleration, water was added to the canister to fill the void around the outside of the IV bags. The void was due to the bags not conforming perfectly with the inside of the canister. This provided a hydrodynamic environment which created equal pressure inside and outside the bags. Without the water, the pressure inside the bag, generated during set-back acceleration, would exceed the pressure outside the bag. The bag would attempt to expand to fill all available volume, and would therefore rupture.

Efforts from testing with the cylindrical shock fixture yielded insight into bag survivability based on packing configurations, air volume, and bag to bag interaction. Only four bags, side by side, would fit into the cylinder. The bags were placed inside the cylinder, two with the ports up and two with the ports down as seen in Fig. 6. The internal canister configuration shown in Fig. 7 is representative of the one piece canister with longitudinal and radial baffle. The rigidity of the Lactated Ringer bags made it difficult to pack the bags into the cylinder. An effort to improve packing ease was made by removing air from the bag via a syringe. This did compromise the port from which the air was removed. The Hespan bags were easier to pack, which may have been a result of having a very small air volume. The results of shock testing reveal that at least one bag out of four, for Hespan, Lactate Ringer's and combinations of the two, would fail as the accelerations neared 10,000 g's.

Figure 6: IV Bag Packing Configuration for the Shock Table

Testing single bags at a time, hydrostatically, revealed that the bags could survive more than 20,000 g's. Unfortunately, the testing could only be repeated a few times since the test fixture became damaged. Based on the results, it was decided that in order to ensure bag survival due to set-back loading, each bag had to be individually contained. This lead to a baffled canister design for the MRP.

In order to test the hypothesis that a baffled canister would improve the survivability of the bags, a new shock fixture test canister was designed and fabricated, see Fig. 7. This new fixture used a longer cylinder with a baffle that separated the volume into four equal compartments. The baffle comprised a long aluminum plate that ran the length of the cylinder, and a perforated aluminum disk that was welded to the middle of the plate. The only type of a bag to be tested was the Hespan bag because of the very small air volume and ease of packaging. This small air volume would not compromise the hydrostatic condition as much as the larger air volume of the Lactated Ringer's bags. The results from the new shock fixture indicated that separating the bags into compartments significantly improved the survivability of the bags under acceleration loading up to 16,500 g's.

With the bags surviving the set-back load in the baffled shock fixture, the gun-launchable version of the canister was to follow. At this point in time, the Savage canister design team had determined the inner diameter of the canister. Therefore, for the gun launch test, the inner diameter of the MRP canister had to be small enough to allow enough wall thickness and still fit into the Savage canister while holding bags. Based on this constraint, time and ease of fabrication, the proof-of-concept gun launch design

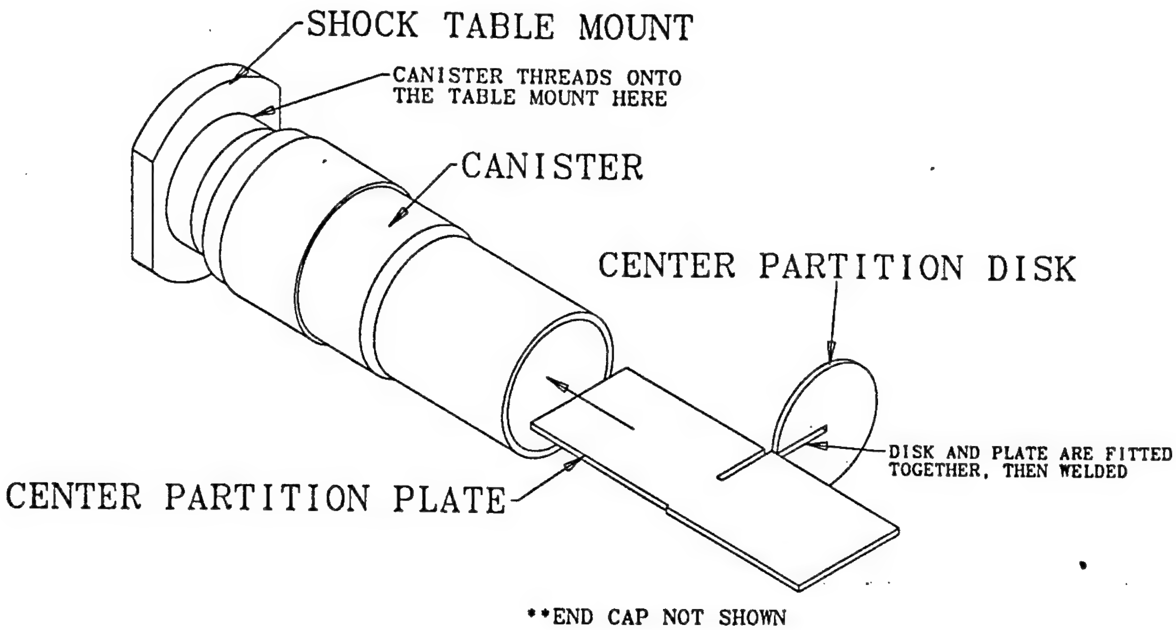


Figure 7: Exploded View of Final Shock Fixture Canister Design

called for two separate, baffled canisters. The size of the canisters left enough room for an aluminum spacer that would simulate the parachute mass. Both canisters and the spacer were keyed to the inside of the M483 artillery shell. Figure 8 displays the MRP two canister design and how the configuration would be loaded in the M483 for the flight tests.

4.3.2.2 MRP Payload Canister Stress Analysis

A three-dimensional, static, finite-element stress analysis was performed on the lower MRP canisters of the final two canister design. It was felt that the lower canister was the more critical structure component of the MRP system, since it would have to not only support itself, but also the load generated by the upper canister. This analysis only investigated the stresses due to set back accelerations which would be simulated by the shock fixture. Integrated Design and Engineering Analysis Software (I-DEAS) developed by Structural Research Corporation (SDRC) was used for the finite element analysis. The configuration consisted of an aluminum 6065-T651 tube that was 5.73 inches long with a 4.54 inch inner diameter and a 0.25 inch wall thickness. End caps, that were 0.625 inches thick, were screwed into both ends of the tube. The end caps were made of aluminum 7075-T651. An aluminum plate, that was 0.125 inches thick, ran down the center of the canister to provide the baffle. This aluminum plate was also made from aluminum 7075-T651. The entire configuration, see Fig. 9 was descritized with 14,597 elements and 19,254 nodes to create the three-dimensional, finite-element model.

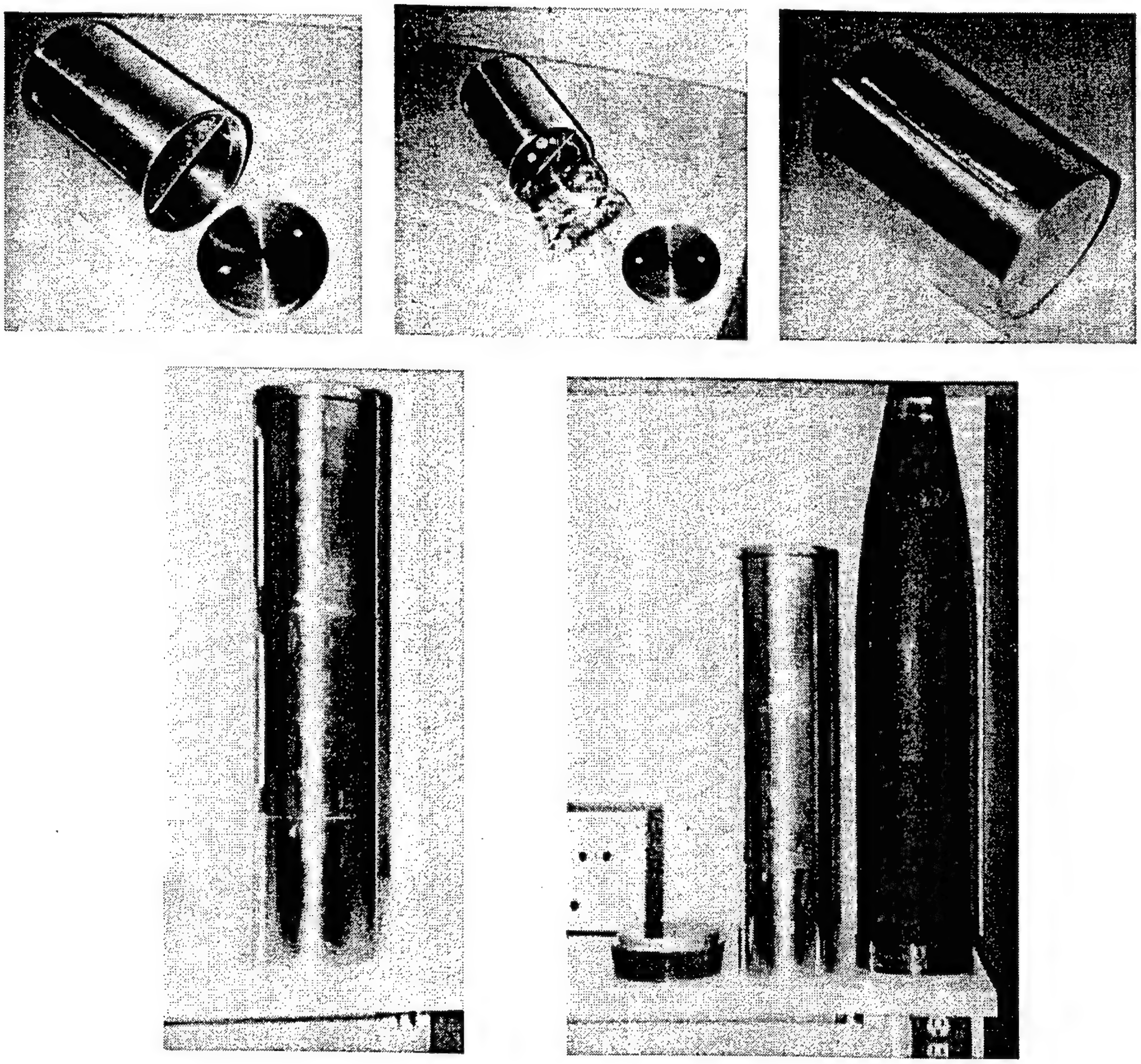


Figure 8: MRP Canister and the Loading Configuration of the M483

The boundary conditions simulated the inertial set-back acceleration loading of the bottom canister, inside the M483 artillery shell. The first boundary condition restrained the base of the canister and applied an 8,000 g acceleration load to the entire can. Although, the sides of the payload canister would typically be supported by the inner wall of the M483 artillery shell, this support was not modeled. Instead, a more severe and conservative loading condition was applied by not restraining the canister sides. Thus, the canister sides had to support themselves. This approach was necessary due to time and computer availability. Another boundary condition consisted of a uniform pressure applied to the top of the canister to simulate the loading due to the top canister under the acceleration g's. Pressure was administered to the inside of the canister to simulate the pressures due to the fluids from the launch accelerations. The pressure that was administered was determined by a simple Bernoulli equation: $P=\rho gh$. Where P equates to pressure, ρ is the density of the fluid, g is gravity or acceleration, and h is the

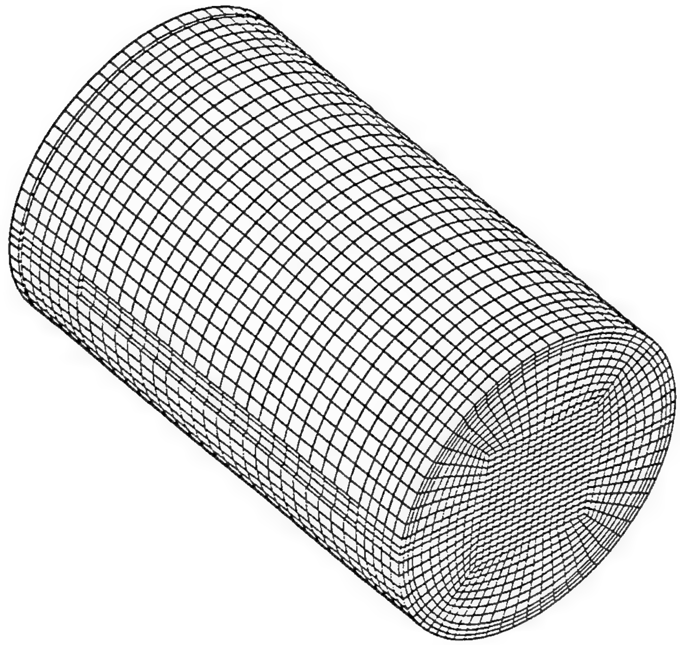


Figure 9: Finite Element Model of Lower Canister of Two Canister Design

height of the column of fluid. The density used was that of water. The pressure gradient due to a spinning fluid was not modeled but will be included in future stress analyses.

The resulting stresses were analyzed using the von Mises stress criterion. The von Mises stress criterion is a theory that specifies that plastic yielding will occur when the combined stresses of a body equal or exceed the tensile yield stress of a material.[9] If the design has extensive areas of plastic yielding, then it is likely to suffer unacceptable deformations, and possibly even fracture in service. The maximum von Mises stresses were found on the bottom of the baffle plate. These stresses were primarily a result of the combined axial loading on the plate. The von Mises stresses at this point are on the order of 40,500 psi. The canister experienced the next highest level of stresses, with a maximum von Mises stress of 28,200 psi. These stresses could be found primarily in the threaded regions.

The conclusion of the stress analysis due to set-back would be that the bottom canister should survive without any significant plastic deformation. The canisters were designed to be fabricated with aluminum 6061-T651 which has a tensile yield strength of 40,000 psi whereas the maximum von Mises stress for the canister was 28,200 psi. The baffle plate, with a maximum von Mises stress of 40,000, was to be fabricated from aluminum 7075-T651, which has a tensile yield strength of 73,000 psi. Since the stress results indicate that the bottom canister should survive not only the 8,000 g acceleration loading, but the loading due to the top canister, one can conclude that the top canister should survive the 8,000 g acceleration loading alone.

4.3.2.3 Shock Fixture Testing

4.3.2.3.1 Description of Shock Fixture

Figure 10 shows a sketch of the Impac 66 HVA shock test machine and some of

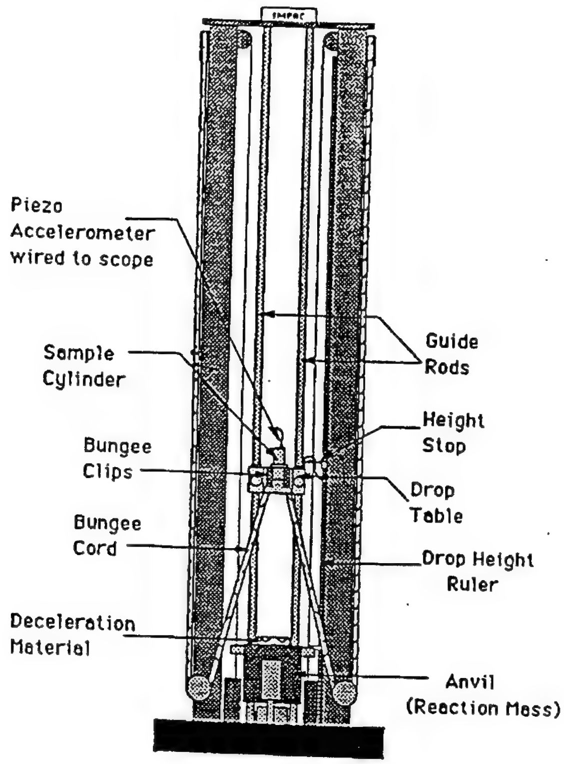


Figure 10: Impac 66 HVA Shock Test Machine

the associated components. This machine is designed for testing specimens at extremely high velocities and/or high accelerations. The MRP shock fixture is bolted to the Drop Table. The table is then pneumatically raised to a desired height. Once the table is released, the Bungee Cord pulls the table onto the Anvil, or reaction mass. A Deceleration Material is placed on the Anvil. This material, such as thick felt sheets, tailors the deceleration impulse. A Piezo Accelerometer and oscilloscope record the shock event. The shock table can safely test specimens at g-levels up to 30,000.

4.3.2.3.2 Shock Fixture Results

Table 3 recounts all of the shock table experiments. The table lists the date, type of bags used, the configuration, and the maximum g-levels. The early tests were performed by placing four bags into a cylindrical shock fixture. Water was added to the fixture to produce hydrostatic loading. An undocumented test was performed on four

bags that did not use water to create a hydrostatic condition. Those bags burst at less than 5,000 g's. Tests 1 through 5 used four, 500 ml Lactated Ringer's bags. Note: due to the limited number of bags, these early tests required that bags were recycled for other tests. As the g-levels approached 10,000 and beyond, one of the bags would typically develop a leak. Tests 6 through 8 were performed with 500 ml Lactated Ringer's bags that had the excess air removed. Air was removed by inserting a syringe into the infusion port and drawing out the air. These bags also failed around 10,000 g's. Tests 9 through 11 utilized 500 ml Hespan bags. Bag failures occurred around 10,000 g's.

Tests 12 through 20 were performed by shocking one bag at a time. This was to determine if the bags could survive without interaction from other bags. The tests showed that fresh bags could survive up to 20,000 g's. Unfortunately, this testing damaged the shock test fixture. Based on their repeated survivability of single bags, a baffle system was designed to provide individual compartments for each bag. A new fixture with a baffle was designed and fabricated for the next tests.

The new shock fixture had a baffle that consisted of a long rectangular plate that ran the length of the cylinder. A thin disk, with slots to allow water to flow axially, and a slot to allow the mating of the disk to the plate, was press fitted into the rectangular plate. This formed a longitudinal and radial baffle, that when fitted into the payload canister, would divide it into four compartments. Allowing the water to flow between compartments was necessary for packaging the bags into the canister and for pressure equalization between compartments during set-back acceleration.

Test number 21 was performed with the new fixture. The bottom bags survived, but the top bags sustained multiple punctures. The top bags appeared to have tried to flowed through the slots in the radial baffle into the bottom compartments. A quick modification was made to block these slots.

Once the bottom bags were loaded, and the baffle was in place, water was poured into the fixture. With the bottom compartment filled, two thin, semi-circular forms were placed on top of the radial baffle. The next test, test number 22, had a maximum g-level of 16,568 g's where three of the bags survived. One of the top bags developed a small pin-hole leak which was believed to be the result of the form pinching the bag. Test number 23 was performed at 14,600 g's. The results were marred by the structural failure in the radial baffle. A new baffle disk was designed and fabricated. The new disk had several small holes to allow water to flow. The disk was also welded to the rectangular plate. When the bags were being loaded for test number 24, semi circular felt wedges were placed on top of the radial baffle to obscure the holes. Test number 24 was performed at 11,190 g's without a single bag failure.

Table 3: Shock Fixture Test Results (page 1 of 3)

TEST #	DATE	BAGS	CONFIG	MAX G's	COMMENTS
1	27/7/1995	LRWA10	BOTTOM	7007	Could only fit 4 bags into tube, 2 bags, side-by-side
		LRWA11	BOTTOM		
		LRWA12	TOP		Mitigator was 0.5" thick. All ports were dry
		LRWA13	TOP		
2	27/7/1995	LRWA10	BOTTOM	9615	LRWA12 IV port failed...the inner membrane was leaking
		LRWA11	BOTTOM		
		LRWA12	TOP		All other ports were dry
		LRWA13	TOP		Note: bags are being recycled.
3	27/7/1995	LRWA14	BOTTOM	10463	LRWA17 failed at a seam. All other bags survived with dry ports.
		LRWA15	BOTTOM		
		LRWA17	TOP		
		LRWA19	TOP		
4	31/7/1995	LRWA30	TOP	13508	LRWA30 failed at a seam. All other bags survived with dry ports.
		LRWA31	TOP		
		LRWA32	BOTTOM		Mitigator consists of 2-0.125" pads
		LRWA33	BOTTOM		NOTE:this was the 2nd test for these bags. The previous test had a max g-level of 12160. Data was accidentally lost
5	31/7/1995	LRWA15	TOP	12509	LRWA15 failed at a seam
		LRWA31	TOP		All other bags survived with dry ports.
		LRWA32	BOTTOM		Duration at 9514 G's: 55 micro-sec
		LRWA33	BOTTOM		
6	31/7/1995	***LRNA20***	TOP	6058	Mitigator consists of 1-.125" pad.
		LRNA21	TOP		Infusion ports of bag 21 have moisture in them.
		LRNA24	BOTTOM		IV ports of all other bags are dry
		LRNA25	BOTTOM		
7	31/7/1995	***LRNA20***	TOP	10837	LRNA31 failed at a seam. All other bags survived.
		LRNA21	TOP		
		LRNA24	BOTTOM		
		LRNA25	BOTTOM		
8	31/7/1995	***LRNA20***	TOP	10947	LRNA20 and LRNA24 failed at the seams. The other bags survived, but with moisture in the IV ports
		LRNA21	TOP		
		LRNA22	BOTTOM		
		LRNA25	BOTTOM		

Table 3 Shock Fixture Test Results (continue, page 2 of 3)

9	31/7/1995	HSP 10	TOP	5123	100% survival, all ports are dry.
		HSP11	TOP		
		HSP12	BOTTOM		
		HSP13	BOTTOM		
10	31/7/1995	HSP 10	TOP	8679	HSP12 and HSP13 IV ports have moisture in them.
		HSP11	TOP		
		HSP12	BOTTOM		
		HSP13	BOTTOM		
11	31/7/1995	HSP 10	TOP	11062	HSP10 failed on the skin of the bag.
		HSP11	TOP		All bags on the bottom of the tube had the IV ports completely filled with fluid.
		HSP12	BOTTOM		
		HSP13	BOTTOM		
12	03/8/1996	LRNA11	SINGLE	12248	SURVIVED
13	03/8/1996	LRNA11	SINGLE	18674	BURST
14	03/8/1996	LRNA10	SINGLE	20059	BURST
15	03/8/1996	LRWA40	SINGLE	20633	Survived. Note: this bag was never shocked before
16	03/8/1996	LRWA41	SINGLE	21145	Survived. Note: this bag was never shocked before Shock fixture is starting to buldge at the base due to internal pressures
17	03/8/1996	LRWA41	SINGLE	15167	Survived. Lowered the shock level
18	03/8/1996	LRWA40	SINGLE	17201	Survived.
19	03/8/1996	LRWA32	SINGLE	20396	Survived. Mitigator is not dampening the shock
20	03/8/1996	LRWA13	SINGLE	22355	Survived. Eventhough the anvil drop height was reduced, the mitigator is not dampening the shock. Shock fixture is now unsafe. A new shock fixture was fabricated. This fixture kept the bags separated with a baffle.
21	01/5/1996	LRWA02B1	BOTTOM	15784	Survived
		LRWA01B2	BOTTOM		Survived
		LRWA02T2	TOP		Multiple Punctures
		LRWA01T1	TOP		Multiple Punctures Punctures are due to baffle design. A modification was made for the next test

Table 3 Shock Fixture Test Results (continue, page 3 of 3)

22	01/5/1996	LRWA03B	BOTTOM	16568	Survived
		LRWA04B	BOTTOM		Survived
		LRWA03T	TOP		Survived
		LRWA04T	TOP		Tiny pin hole found. Believed to result from pinching from baffle modification
23	01/5/1996	LRWA05B1	BOTTOM	14600	Small pin found
		LRWA06B2	BOTTOM		Survived
		LRWA05T1	TOP		Multiple punctures
		LRWA05T2	TOP		Multiple punctures. Baffle has structurally failed. The baffle has to be redesigned and fabricated.
24	06/6/96	HSP1T	TOP	11190	All bags survived. This test used a modified baffle design
		HSP2T	TOP		
		HSP1B	BOTTOM		
		HSP2B	BOTTOM		

LRWA##: this stands for Lactated Ringers with air
LRNA##: this stands for Lactated ringers with no air
HSP##: this stands for Hespan

Observing the bags consisted of observing the skin, seams, the infusion port, and the IV ports.
The infusion port is the "nipple" with the rubber end cap.
The IV port is the "nipple" with the plastic endcap.

On the Ringer bags that had the air extracted, air was removed via syringe needle injected into the infusion port.

4.3.2.4 Phase 1 Conclusions and Summary

The purpose of shock testing the IV bags was primarily to determine whether or not the bags would survive the high g accelerations due to gun launch loads. The secondary objective was to determine an effective means of packaging the bags. The shock table testing indicated that four bags packed into a cylinder, with water to fill the remaining void in the cylinder, (no baffle) cannot survive g-levels above 9000 g's. Further testing proved that the single bag configuration could survive high g accelerations of 20,000 g's. At this point, it was concluded that single bags, or bags in separate compartments, had a better chance of surviving high g shock. Shock testing revealed that separating the bags with a baffle allowed the bags to survive an excess of 10,000 g's. This revelation led to the multi-canister proof-of-concept test which involved placing two canisters, and an aluminum spacer, into an M483 artillery shell. It was easier to fabricate two separated canisters than to fabricate a single long one. Each canister had a baffle plate that divided the volume of the canister into two equal volumes. The aluminum spacer filled the rest of the void in the shell and provided a dummy mass that represented a parachute payload.

4.3.3 Phase 2 - Experimental Stability Test

4.3.3.1 Description of the Laboratory Flight Simulator for Non-rigid Payloads (Spin Fixture)

The Spin Fixture[10] at ERDEC, is a unique apparatus that can simulate the combined spin and coning (nutation or fast precession) motion of an actual projectile in flight, and can determine the effects of this motion on a full scale 155mm artillery projectile canister and payload. Figure 11 shows a typical Spin Fixture test setup. The canister is attached to the simulator frame by bearings, allowing it to spin freely about its longitudinal axis, while the frame is forced to spin about a vertical axis. The canister spin rate is generated by an air turbine attached to the bottom of the canister's lower bearing support, and driven by a compressed air nozzle attached to the frame. A belt driven electric motor provides the frame's spin rate, and thus the corresponding coning rate. Typical projectile flight spin (0-12,000 rpm) and coning rates (0-600 rpm) can be generated on the fixture. This results in the canister assuming the desired simultaneous spinning and coning motion similar to that of the projectile in flight. The payload thus experiences the basic inertial environment it would have in flight and can respond in the same dynamic sense. The Spin Fixture can accept a large variety of different canister geometries and sizes encompassing a broad range of artillery projectile calibers. The mass of the fully loaded canister can be as large as 45 kg. Canister spin rates up to 12,000 rpm and coning rates of 600 rpm can be achieved. The canister can be set to one of five fixed coning angles, 0 to 20 degrees in 5-degree increments. Tests are conducted over a range of constant coning rates at each fixed coning angle, thus encompassing spin and precession motion corresponding to various firing zones and projectile flight yaw angles. Although the fixture measures the liquid despin moment, it has been shown by

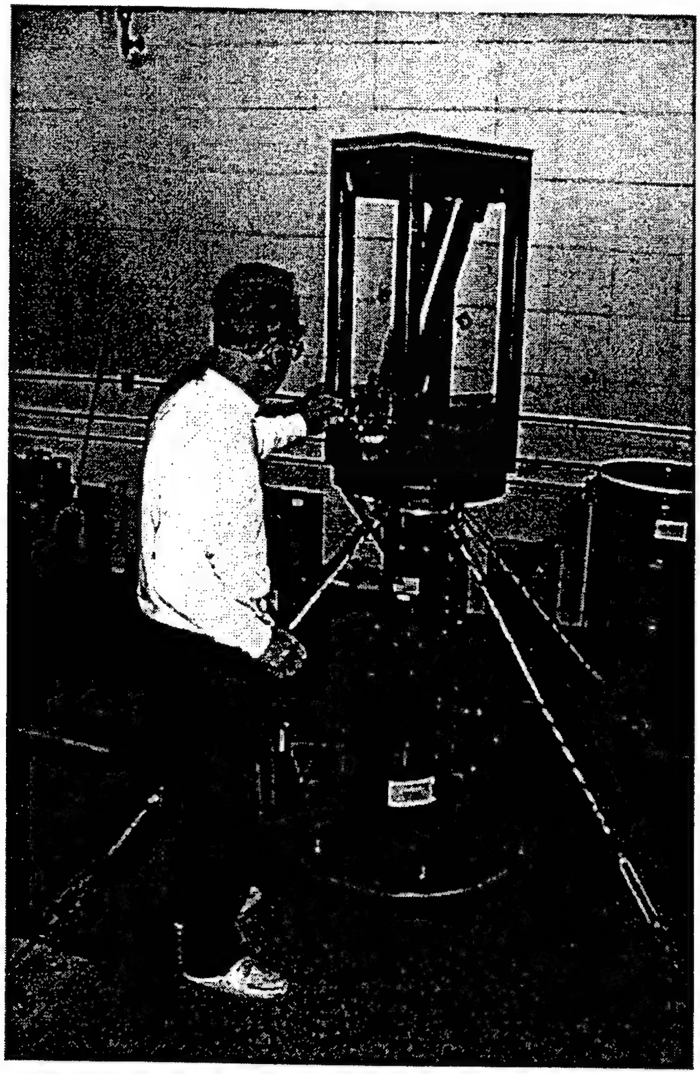


Figure 11: J. Molnar Adjusts the Laboratory Test Fixture for Non-Rigid Payloads

Murphy[11] that liquid despin moment and the liquid induced yaw moment are related through a simple expression. Thus, once the despin moment has been measured, the destabilizing yaw moment can be calculated.

Various types of instrumentation can be incorporated in the simulator to measure different phenomena of interest. Of particular importance is the despin moment created by the movement of certain non-rigid payloads in response to the flight motion of the projectile. The magnitude of this despin moment can be easily and accurately measured on the Spin Fixture, and is used to assess the potential of the payload to create a projectile flight instability. The fixture can also be used in experimental investigations of the detailed behavior of liquid fills with regard to both flight instabilities and mixing characteristics.

The test fixture is limited to simulating the steady state angular motion of a projectile in flight. The transient spin-up of the projectile during launch cannot be simulated. Aerodynamic forces, (e.g. drag and lift) as well as the effect of gravity are ignored, since typically the angular accelerations are orders of magnitude greater than the aerodynamic and gravity effects. The test fixture is most sensitive in measuring viscous type instabilities, but experiments have shown that the fixture can detect resonance instabilities.[12]

4.3.3.2 Typical Spin Fixture Test Procedure

With a test canister geometry and IV bag payload both selected, the bags are loaded into the canister, water is used to fill the voids around the bags, the canister's end caps are screwed on, and the canister is installed in the Spin Fixture at the desired fixed coning angle. A typical test run begins by spinning the payload canister to approximately 10,000 rpm using an air turbine. As the canister spins up, the electric motor controlling the coning (nutation) rate is turned on. The coning rate is gradually increased to the predetermined value, typically 200, 300, 400 or 500 rpm, respectively. Once the desired test coning rate is achieved, the air is shut off to the turbine while the electric motor maintains a constant coning rate. Thus for a given test run, both the coning angle and rate are held constant. With the air turned off to the turbine, the payload canister despins under a combination of aerodynamic, frictional, and payload forces and moments. The despin is recorded versus time using a computer controlled data acquisition system. Approximately every second the canister spin rate is recorded. Once the canister spin rate decreases to a cutoff limit, 200 rpm (selectable), the data acquisition system stops taking data, stores the raw data, and reduces it to a payload despin moment.

The first step of the data reduction process begins with a plot of the raw spin data versus time, Fig. 12. The raw data plot is used to verify that the recorded data appears normal, and that there were no instrumentation or fixture malfunctions during the run. The slope of the despin curve is calculated at each data point. The resulting time rate of change of the canister spin rate is then multiplied by the moment of inertia of the empty (i.e., no liquid payload) canister to yield the total despin moment. The friction moment, which takes into account the friction and aerodynamic forces/moments on the empty canister, is subtracted from the total moment. The resulting moment is the contribution of the liquid payload, and is called the despin moment. A typical plot of the resulting Total, Friction and Despin Moments are shown in Fig. 13

The friction data used in the reduction process are obtained in a similar process as performing an actual data run, with the exception that the canister does not contain a liquid payload. A different set of friction data is required for each coning angle

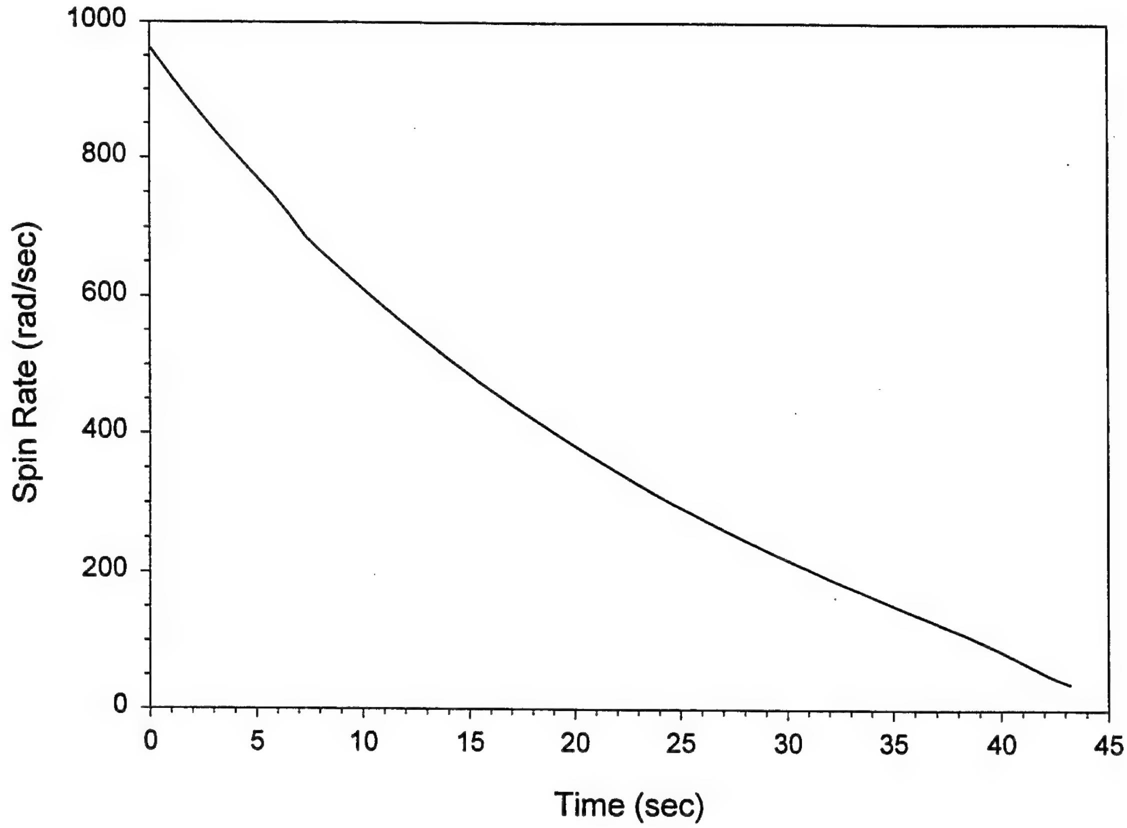


Figure 12: Typical Spin Fixture Raw Despin Trace

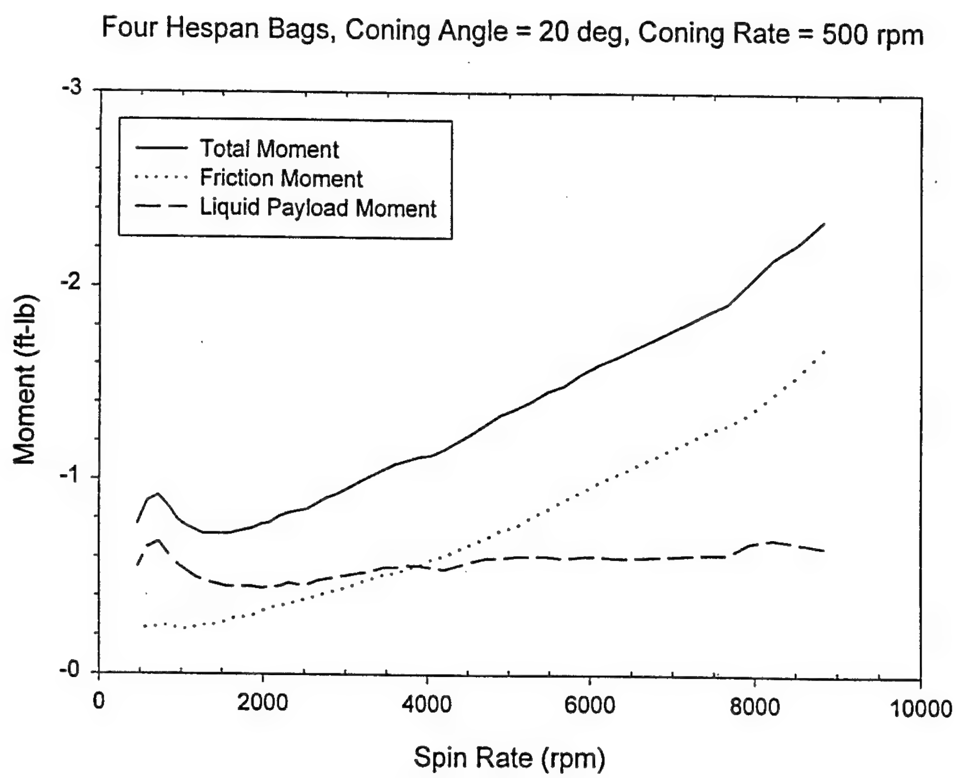


Figure 13: Typical Spin Fixture Result Plot

and coning rate combination. In other words, if four coning angles and four coning rates were being investigated, then a total of sixteen friction data sets would be necessary. The friction results are stored in separate files which are identified by coning angle and rate. The appropriate friction file is then automatically selected during the data reduction process of a test run.

4.3.3.3 Spin Fixture Test Plan

The original test plan called for the testing of one payload canister and one type of IV fluid. Due to the complexity of designing the canister to protect the bags during firing setback, and the availability of both Hespan and Lactated Ringer's IV fluids, the test plan was altered to accommodate several payload configurations. The test parameters were setup to cover the flight characteristics of a transonic launch, i.e., a projectile spin of 6,000 rpm and coning rate of 500 rpm. Table 4 contains a list of all configurations tested. Tests 3742 to 3762 used the initial one canister design, while tests 3766 to 3771 were conducted with the modified two canister design.

The original single canister was a one piece cylindrical outer container with a internal baffle that quartered the inside of the canister into roughly equal volumes. The baffle system split the canister longitudinally in half and in half lengthwise. The lengthwise baffle was slotted to allow for the surrounding water packing to flow freely between the top and bottom chambers. The canister held four 500 ml IV bags, two on the bottom and two on the top. Due to problems identified during the shock testing phase of this study, it was determined that a two-canister design provided the necessary protection to survive the gun launch setback environment. So instead of one long canister, two shorter canisters of half the original length were designed. The two canisters were capped at both ends, thus providing complete independence from each other. A longitudinal baffle divided each canister into two compartments. Due to scheduling and funding constraints, a new two piece canister could not be fabricated for the spin fixture tests. Instead, the original one piece spin fixture canister used in tests 3742 to 3762 was modified to approximate the internal configuration of the two piece design. There was not sufficient length available in the original canister to accommodate the added length of the two-canister configuration caused by the additional end caps that separated the two canisters. Since it was possible to match the internal volume of the canisters, it was felt that the overall length difference would not adversely affect the results.

The first set of tests (3742 to 3751) using Hespan, were extremely comprehensive covering three coning angles (10, 15 and 20 degrees) and four coning rates (200, 300, 400 and 500 rpm). After verifying the typical trends of a liquid fill payload, meaning that as the coning angle and/or coning rate decreases the liquid induce despin moment corresponding decreases. After test number 3752 the majority of the experiments were conducted at the worst case conditions of 20 degrees coning angle. Besides the two-canister configurations, three IV bag arrangements were tested: four Hespan, four Lactated Ringer's, and two Hespan (on bottom) and two Lactated Ringer's (on top).

Table 4: Spin Fixture Test Plan

Test #	Payload Configuration Tested	Coning Angle	Coning Rate
3742	Can 1, 4 Hespan 850 ml water	20	500
3743	Can 1, 4 Hespan 850 ml water	20	400
3744	Can 1, 4 Hespan 850 ml water	20	300
375	Can 1, 4 Hespan 850 ml water	20	200
3746	Can 1, 4 Hespan 850 ml water	15	500
3747	Can 1, 4 Hespan 850 ml water	15	400
3748	Can 1, 4 Hespan 850 ml water	15	300
3749	Can 1, 4 Hespan 850 ml water	10	500
3750	Can 1, 4 Hespan 850 ml water	10	400
3751	Can 1, 4 Hespan 850 ml water	10	300
3752	Can 1, 2 Hespan Bottom, 2 Ringers Top	20	500
3753	Can 1, 2 Hespan Bottom, 2 Ringers Top	20	400
3754	Can 1, 2 Hespan Bottom, 2 Ringers Top	20	300
3755	Can 1, 2 Hespan Bottom, 2 Ringers Top	10	500
3756	Can 1, 2 Hespan Bottom, 2 Ringers Top	10	400
3757	Can 1, 2 Hespan Bottom, 2 Ringers Top	10	300
3758	Can 1, 4 Lactated Ringers	20	500
3759	Can 1, 4 Lactated Ringers	20	400
3760	Can 1, 4 Lactated Ringers	20	300
3761	Can 1, 4 Lactated Ringers, Repeat of 3759	20	400
3762	Can 1, 4 Lactated Ringers, No baffle	20	500
3766	Can 2, 4 Lactated Ringers	20	500
3767	Can 2, 4 Lactated Ringers	20	400
3768	Can 2, 4 Lactated Ringers	20	300
3769	Can 2, 4 Lactated Ringers	10	500
3770	Can 2, 4 Hespan	10	500
3771	Can 2, 4 Hespan	20	500

In addition, test 3761 was a repeat of 3759 which investigated the effect of damaged bags, versus new bags. It was assumed, based on earlier tests that the Lactated Ringer's bags in test 3759 were damaged before the test was performed, so test 3761 was conducted with four new Lactated Ringer bags and the results compared and showed very good agreement. Test 3762 was conducted without the internal baffle, in order to determine the effect of the baffle on the liquid despin moment, and for use with possible future packaging arrangements. In all 27 test were performed on two-canister configurations, and three IV bag arrangements. All tests were performed with four IV bags and the surrounding voids filled with water.

4.3.3.4 Spin Fixture IV Bag Survivability

All IV bags tested, both Hespan and Lactated Ringer's, showed a considerable increase in external damage above 10 degrees coning angle. Higher coning rates also attributed to an increase in external bag damage, but was not as severe as the coning angle. Most bags were completely destroyed during testing at a 20 degree coning angle. For the 15 degree coning angle tests the bags exhibited fewer failures, with typical damage being limited to delamination of the thin plastic printed label from the thicker plastic bag. Bags tested at 10 degrees coning angle showed little or no external damage. Based on these observations it was felt that the bags should survive the flight, since in a stable projectile any coning angle above 10 degrees would be quickly dampened.

4.3.3.5 Spin Fixture Test Results and Analysis

As previously mentioned, the spin fixture tests were set up to simulate a transonic launch from a worn gun tube. Typically, for a M483A1 projectile, the "worst case" or critical flight condition occurs over the transonic flight regime. The projectile is aerodynamically unstable, and requires spin to produce a gyroscopic effect which provides an aeroballistic stability. In the transonic regime, the aeroballistic stability is at a minimum and if the liquid payload destabilizing moment is greater than the projectile's aeroballistic stabilizing moment, the round will be unstable for that flight condition. Based on prior instrumented flight tests and spin fixture studies, an empirical boundary was established for the M483A1 with a standard 0.257 caliber base. Thus it could be predicted that any liquid filled projectile for this M483A1 configuration would have a stable flight if it produced a liquid despin moment less than 0.35 ft-lb[13] It must be emphasized however, that this empirical boundary is only for a M483A1 projectile with a standard base fired at a Zone 4 (transonic) flight condition. If these parameters are not met, then the 0.35 ft-lb boundary is not valid and another stability boundary would have to be established.

Cross plots of the results were generated to identify interdependencies between the various parameters tested. In Fig. 14, the liquid despin moments for a four Hespan bag configuration in the original single piece canister at a 20 degree coning angle are plotted against spin rate for different coning rates. Note that the bump in the data around 7000 rpm is due to a mechanical resonance in the spin fixture, and is not caused by any

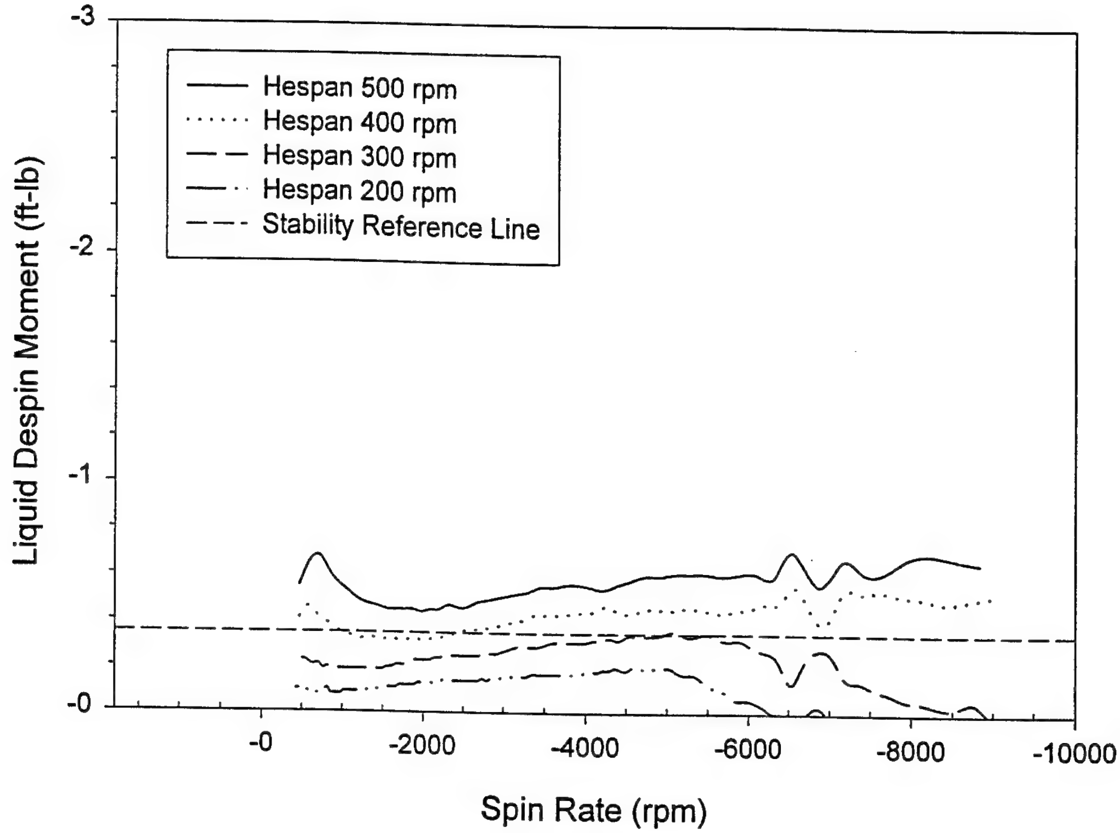


Figure 14: Despin Moment vs. Spin Rate as a Function of Coning Rate for Hespan, Coning Angle=20 degrees, Canister Configuration 1

liquid payload effect. Figure 14 illustrates the normal affect of coning rate on the liquid induced despin moment. That is as the coning rate decreases, for a constant coning angle, the despin moment also decreases. A four Hespan bag payload in canister configuration 1 at 20 degrees coning would achieve a stable flight for only coning rates less than 300 rpm. In other words, for the transonic launch condition and a corresponding 500 rpm coning rate, the four bag Hespan payload would be unstable at a 20 degree yaw coning motion.

Figure 15 shows the results of the four bag Lactated Ringer's configuration under the same test parameters as the Hespan. Comparing Figure 15 (Ringer's) to Figure 14 (Hespan) at the higher coning rates, Ringer's generates larger despin moments. From a stability perspective, a four bag Ringer's configuration, will only be stable for coning rates under 300 rpm. Thus as in the case of the Hespan, the Ringer's filled projectile for high angles of yaw was unstable.

Next the effects of reducing the coning angle on the magnitude of the despin moment are presented in Figure 16. As expected, as the angle decreases the resulting despin moment also decreases which is shown in Fig. 16 for the four Hespan bag configuration. Thus, Hespan should achieve a stable flight if the projectile's coning angle remains below 10 degrees. Also included in Fig. 16 is the 20 degree coning angle test results for Lactated Ringers which shows a despin moment approximately double that of the Hespan for the same conditions.

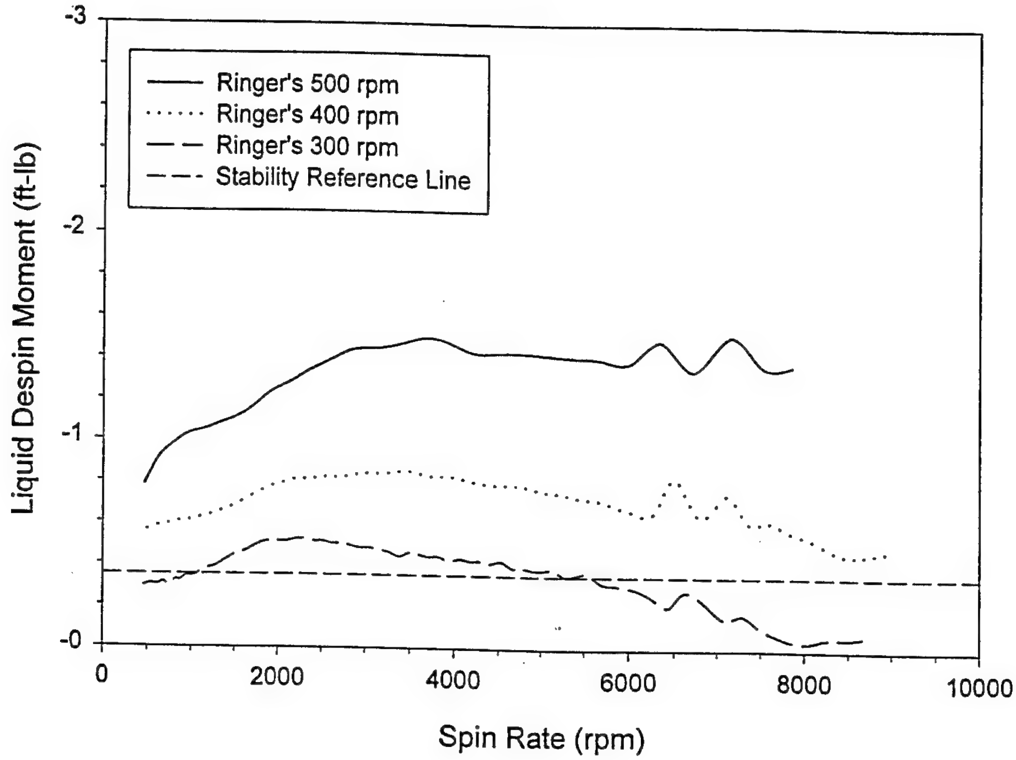


Figure 15: Despin Moment vs. Spin Rate as a Function of Coning Rate for Lactated Ringer's Coning Angle = 20 degrees, Canister Configuration 1

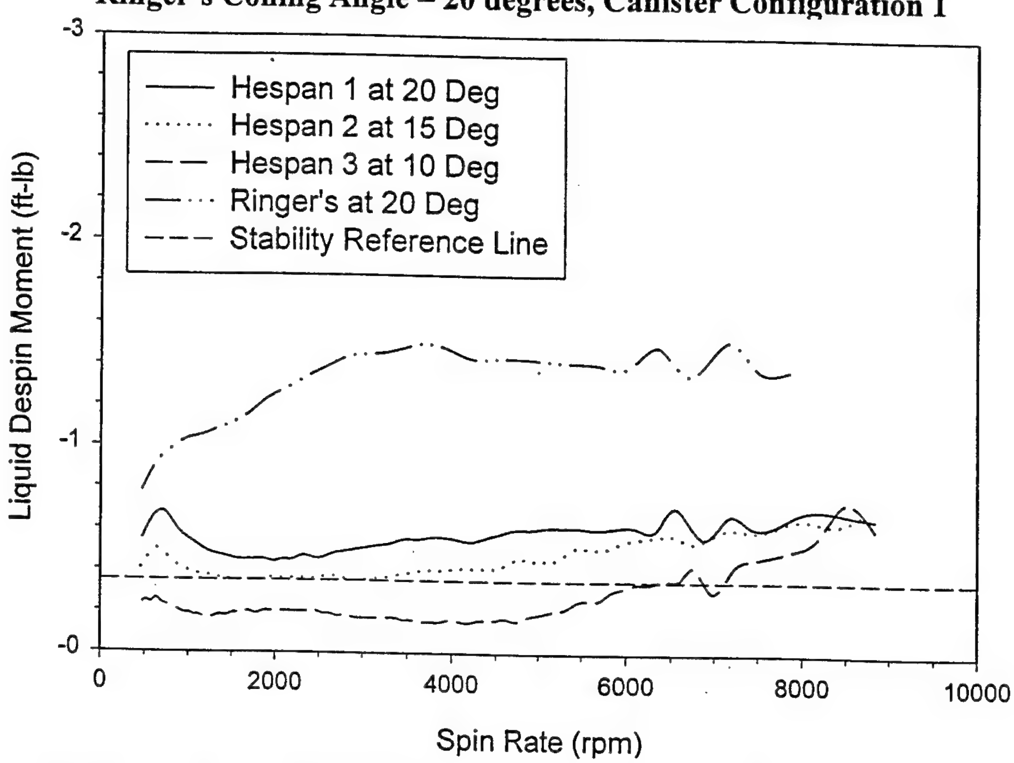


Figure 16: Despin Moment vs. Spin Rate as a Function of Coning Angle for Hespan and Lactated Ringer's, Coning Rate = 500 rpm, Canister Configuration 1

A cross plot comparing the different internal configurations is presented in Fig. 17. These tests all used the one piece canister design. The different internal

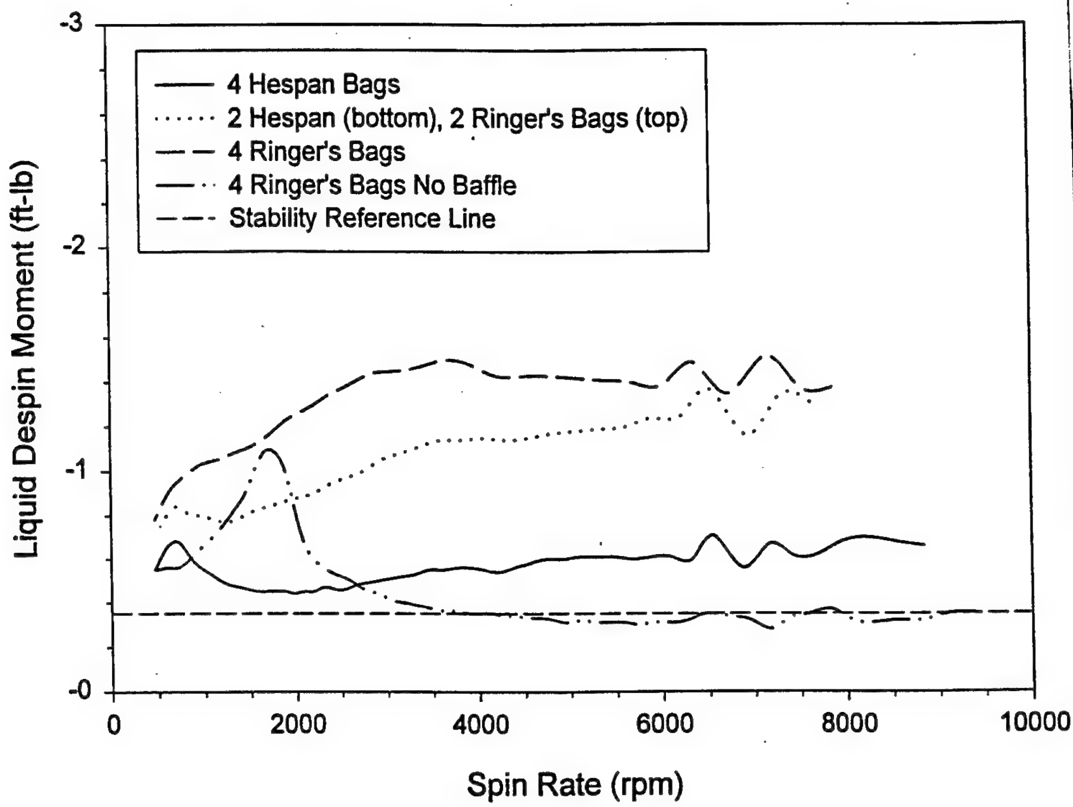


Figure 17: Despin Moment vs. Spin Rate as a Function of Different Internal Configurations, Coning Angle = 20 degrees, Coning Rate = 500 rpm, Canister Configuration 1

configurations tested included: four Hespan bags, four Lactated Ringer's bags, two Hespan and two Lactated Ringer's bag combination, and four Lactated Ringer's bag without the internal baffle arrangement. Except for the no baffle case, all the configurations were unstable. The greatest liquid despin moment is generated by the configurations containing Lactated Ringers. The most interesting point indicated by this plot, is the influence of the baffle on the despin moment. The no baffle Lactated Ringer's configuration generated approximately a quarter of the liquid despin moment that the Ringer's with a baffle configuration produced. This would indicate that the baffle has a very strong affect on the instability of this configuration.

The final set of spin fixture test runs were completed on the two canister configuration. The corresponding results for Lactated Ringer's and Hespan for both a 10 and 20 degree coning angle at a 500 rpm coning rate are shown in Fig. 18. Lactated Ringer's in the two-canisters design generated a substantially higher despin moment as compared with the single canister. On the other hand, Hespan generated a slightly lower despin moment in the two piece canister when compared to the single canister. From these results it was predicted that a Hespan payload should experience a stable flight as long as the yaw angle stayed below 10 degrees.

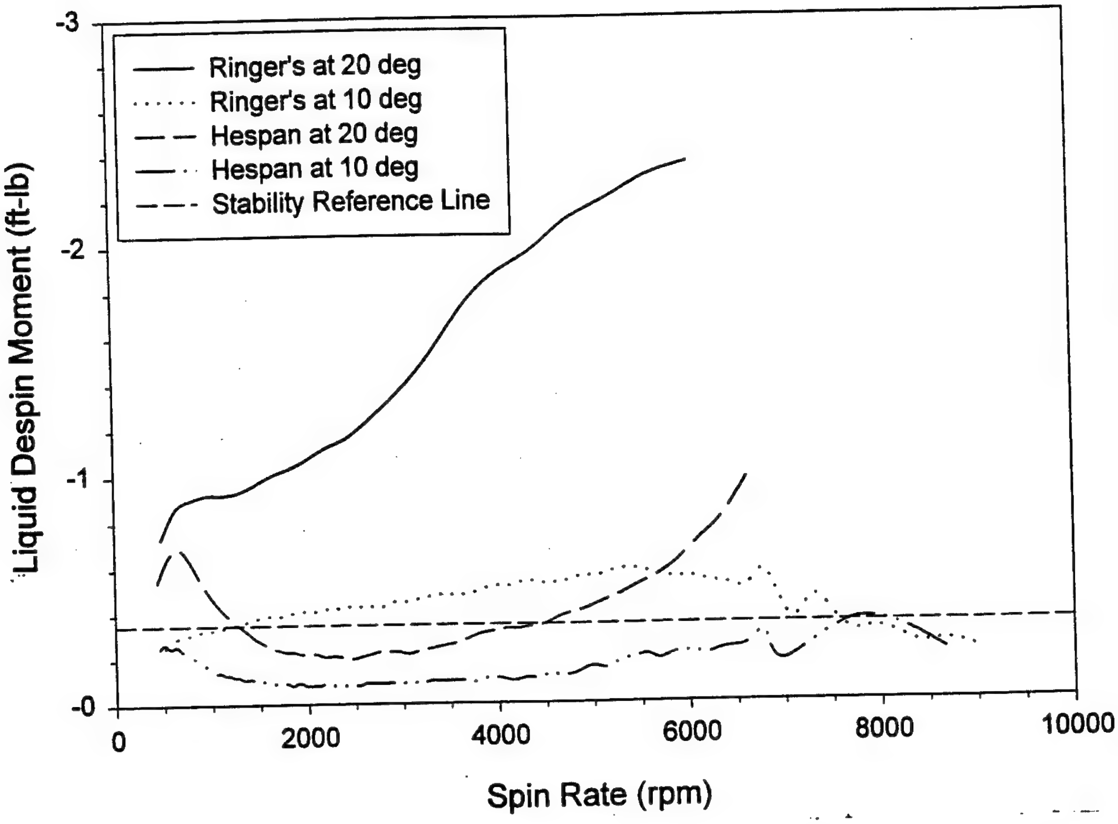


Figure 18: Despin Moment vs. Spin Rate as a Function of Coning Angle for Hespan and Lactated Ringer's, Coning Rate = 500 rpm, Canister Configuration 2

4.3.3.6 Stability Test Results and Recommendation for the Flight Test Phase

One of the more surprising results from this study was that there existed in some instances a factor of three difference in the magnitude of the despin moment between Hespan and Lactated Ringer's for the same test conditions. From past experience, only after the liquid payload's viscosity had been changed by orders of magnitudes, did an appreciable change in liquid induced despin moment occurred. For this study, the rheological properties of Hespan and Lactated Ringer's are almost identical. Overall, the results indicate that for the worst case transonic flight condition, and for coning angles under 10 degrees, a four Hespan bag payload should yield a stable flight for both canister configurations. A Lactated Ringer's filled projectile would however be unstable for a transonic launch condition.

Another observation of the spin fixture results indicates that the internal baffle used to divide the canister into four compartments, may be a major contributor to the despin moment. A no baffle configuration of the single piece canister, test number 3762 (see Table 4, and Fig. 17), showed a substantial decrease in liquid despin moment. At this time it is not known which baffle, longitudinal or radial, had the most affect on the stability. Additional testing would be required to determine the contributions of each baffle. In the two-canister design, the radial baffle has been replaced with canister end

caps, so the only option for that configuration would be to remove the longitudinal baffle from each canister. Shock fixture tests would be required to determine if the IV bags could survive setback in the two canister design, without the central baffle. Consideration of the no baffle option would also have to include a study of the survivability of the bags during projectile spin up. Without a baffle, the IV bags would rub against the inner surface of the projectile as the shell spun up during launch with the possibility of the bags being destroyed before the shell and IV bags achieved the same steady state spin rate.

4.3.4 Phase 3 - Flight Test

4.3.4.1 Overview of Flight Test

The purpose of the Flight Test Phase of this study was to provide a final assessment of the stability of a full up MRP based on the supplemental findings from Phases 1 and 2. The main goal of the test was to determine the stability of the MRP, and not to demonstrate the complete functionality of the resupply system. Because the standard projectile fuze was replaced with a Yawsonde device to record the flight motion of the projectile, expulsion of the MRP payload was not possible. Through the use of yawsonde telemetry and radar, the complete flight motion of the projectiles were recorded and analyzed. A total of five M483A1 projectiles were prepared for these tests. Two of the five were solid rounds which were used as flight standards or experimental controls. The remaining three rounds contained the two canisters with baffle design, with a total of four 500 ml Hespan bags. The flight tests took place at the Army Research Laboratory's Transonic Range at the Aberdeen Proving Ground in mid October, 1996.

4.3.4.2 Description of Yawsonde

Yawsondes are instruments which look like and replace the conventional projectile fuze. Yawsondes contain two or more sensors which determine the relative motion of the projectile with respect to the sun. Figure 19 provides a schematic of the internal layout of a yawsonde. An FM/FM telemetry system transmits the sensor data from the yawsonde to a ground station. The raw data appears as a series of positive and negative pulses which is reduced to a solar aspect angle (σ_N or Sigma N) and the Eulerian roll angle ($\dot{\varphi}$ or Phi Dot) of the projectile. For small projectile angles of attack, the value of $\dot{\varphi}$ is approximately equal to the projectile's

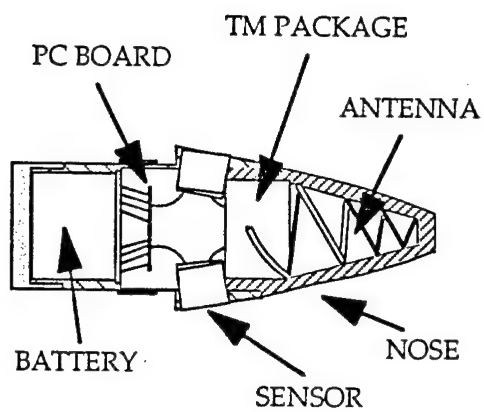


Figure 19: Yawsonde Schematic

spin rate. Further analysis of the yawsonde data can be performed to obtain the epicyclic motion and certain aerodynamic and liquid fill characteristics. For the purpose of this study, only the raw yawsonde plots are presented. The stability of the projectile is easily ascertained from the raw yawsonde plots.

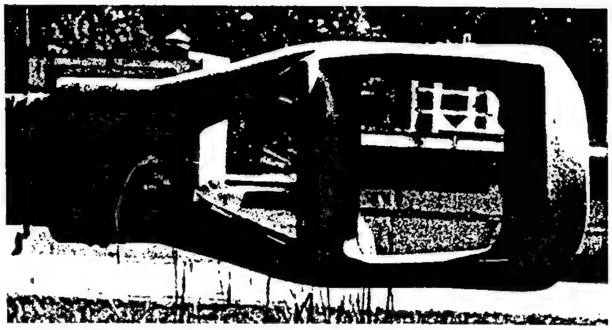
Yawsonde tests require the sun to be in proper alignment with the line of fire. Depending on the time of year, and test location, a firing window can be established that dictates when the flight tests can be conducted. Projectiles fired outside of this window, run the risk of having the yawsonde not report part of the flight. For these tests the firing window occurred between sunrise and 1130 hours.

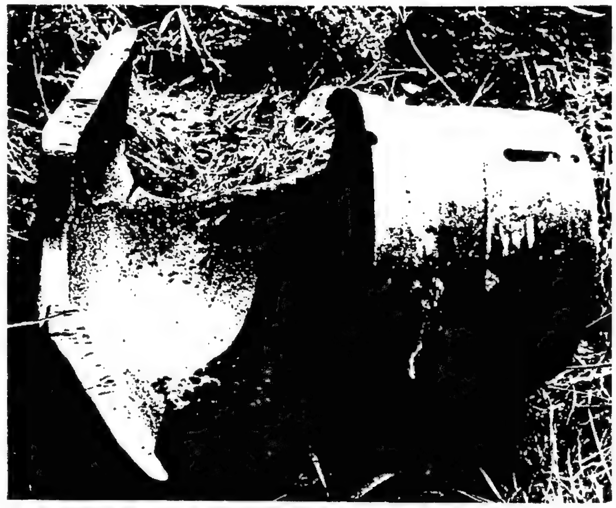
4.3.4.3 Description of Transonic Range

The flight tests were conducted at the ARL Transonic Range at the Aberdeen Proving Ground. The projectiles were shot from a M198, 155mm cannon which is shown in Fig. 20. Various muzzle brakes were used to induce projectile yaw as the round exited the barrel. A standard full muzzle brake will typically impact 2 to 3 degrees of yaw to a

Figure 20: M198, 155mm Cannon at APG Transonic Range

projectile. The half muzzle brake simulates the effects caused by a worn gun tube, and can produce yaw angles of 5 to 10 degrees. Additional plates can be added to the half muzzle brake to increase the asymmetric muzzle blast effects and generate yaw angles of 10 to 15 degrees. For these tests, full and unmodified half muzzle brakes were used. Additionally, one shot was made without any muzzle brake. The full and half muzzle brakes used during these tests are presented in Fig. 21.





FULL **UNMODIFIED HALF**

Figure 21: M198, 155mm Cannon Full and Unmodified Half Muzzle Brakes

Projectile tracking was performed by a Weibel 1000 Tracking Doppler Radar. The Weibel recorded the velocity and position of the projectile with respect to time. Two main purposes were served by the radar, one was to determine the muzzle velocity of the projectile, and the second was for range safety. It was important to track the projectile to verify that it did not impact outside of the Aberdeen range boundaries, thus possibly endangering other personnel. Additionally, still and video cameras recorded the test setup and firings. A smear camera recorded the projectile as it exited the gun tube to confirm that the projectile had not been damaged during launch.

4.3.4.4 Test Plan

Five M483A1 projectiles were prepared with yawsondes for the MRP flight test. Of the five, two had solid payloads and three had four bags each of 500 ml Hespan with the surrounding void filled with water. Because the full-up MRP rounds weighed approximately 79 lb, and a typical 155mm round weighs approximately 100 lb, the slug filled solid rounds were designed to match the physical properties of the MRP projectiles. Table 5 presents the physical properties of the five projectiles. The slug filled rounds were then used as a combination: warmer, propellant check, and flight standard. Table 6 documents the test plan for the MRP flight test. The solid rounds were shot first to establish the correct propellant charge needed to obtain a muzzle velocity of

Table 5: **Flight Test Projectiles Mass Properties**

Projectile	Mass (kg)	Length (m)	C.G. from Base (m)	Trans Moment of Interia ($kg \bullet m^2$)	Axial Moment of Interia ($kg \bullet m^2$)
Warmer #1	35.8	0.9025	0.3378	1.502	0.136
Warmer #2	35.7	0.9022	0.3378	1.497	0.136
MRP #1	35.5	0.9024	0.3423	1.415	0.137
MRP #2	35.7	0.9024	0.3424	1.413	0.139
MRP #3	35.6	0.9024	0.3438	1.409	0.138

Table 6: Flight Test Plan

Projectile	Fill	Muzzle Brake	Quadrant-Elevation (degrees)	Muzzle Velocity (m/sec)
Warmer #1	Solid	Full	45	330
Warmer #2	Solid	Half	45	330
MRP #1	Four 500 ml Hespan, Water filled void	Half	45	330
MRP #2	Four 500 ml Hespan, Water filled void	Half	45	330
MRP #3	Four 500 ml Hespan, Water filled void	None	45	330

approximately 330 m/s (transonic velocity). The recorded flights of the solid projectiles were used to verify that the reduced weight created no adverse aerodynamic effects on the stability of the projectile. The MRPs were then fired with various amounts of muzzle induced yaw and their flight profiles recorded.

4.3.4.5 Flight Test Results

The flight test results are summarized in Table 7. Warmer #1 (solid) was fired using a full muzzle brake on 16 October 1996. This projectile achieved a slightly lower than desired muzzle velocity (295 m/s), sustained a stable flight. The round flew for 32

Table 7: **MRP Flight Test Results**

Projectile	Muzzle Brake	Muzzle Velocity (m/sec)	Flight Time (sec)	Stability	Range (m)
Warmer #1	Full	295	32	Stable	–
Warmer #2	Half	337	35	Stable	8100
MRP #1	Half	336	18	Unstable	2950†
MRP #2	Half	337	20	Unstable	3500†
MRP #3	None	338	23	Unstable	5030

† The radar did not track the projectile for full range. The round was lost near the end of its flight

seconds but no radar range data were obtained. The propellant charge was increased but due to test window constraints, no further shots were made that day. Weather conditions prohibited firing the four remaining projectiles until 21 October 1996.

Warmer #2 was fired using a half muzzle brake and obtained a correct muzzle velocity of 336 m/s. This round was also stable and flew its full range (8,100 m) in 35 seconds. A smear photograph of Warmer #2 is shown in Fig. 22, and is representative of all the projectiles fired during this flight test. The time of flight was three seconds longer for Warmer #2 than for Warmer #1 which was due to the higher muzzle velocity. The spin decay and yaw history, σ_N, for Warmer #2 is shown in Fig. 23 and is typical for a 155mm projectile. The shell exited the gun tube with approximately 3 degrees of yaw which grew slightly to 5 degrees. From the yawsonde trace it can be seen that the nutation (fast mode) damped out, and the precession (slow mode) established a limit

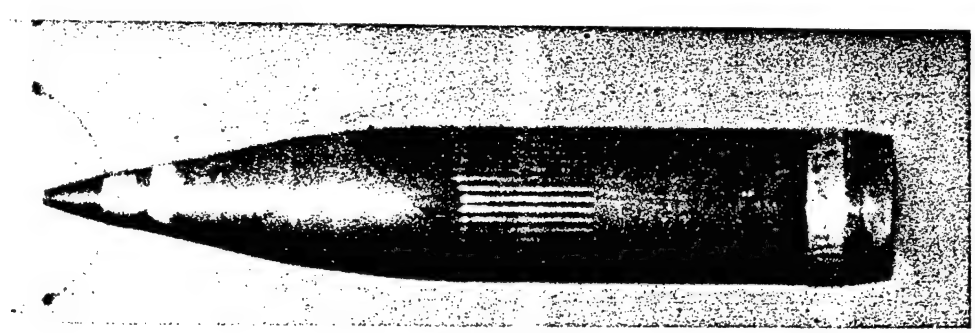
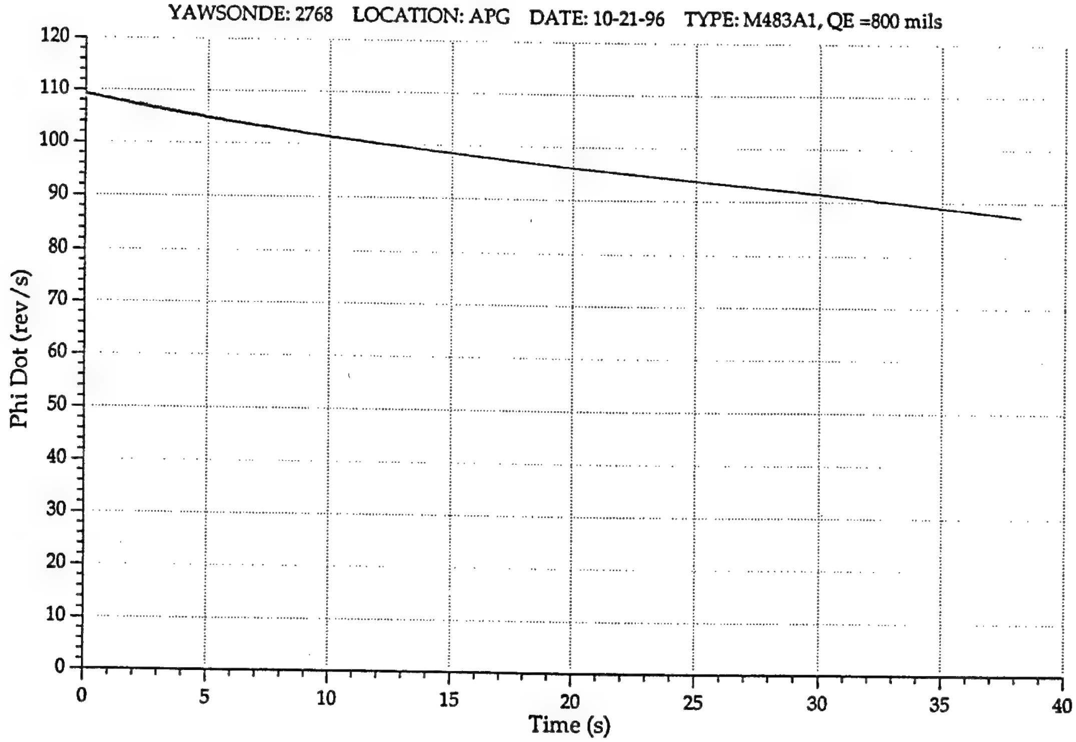


Figure 22: Warmer #2 Smear Photograph at Muzzle Exit



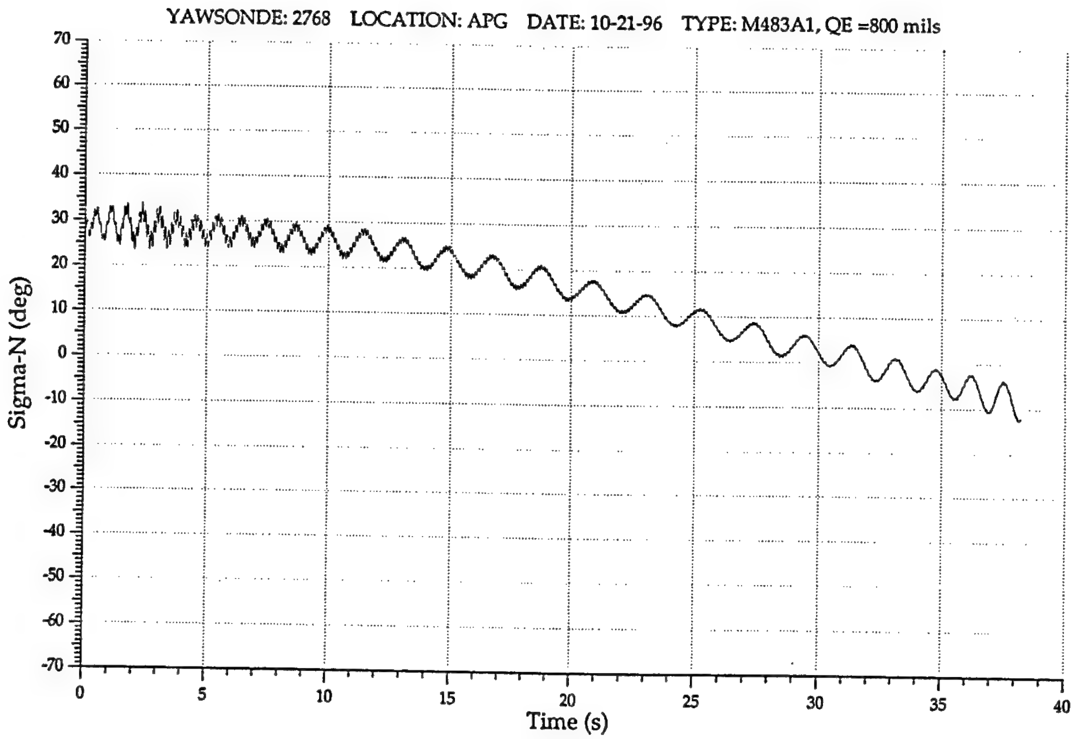


Figure 23: Spin Decay (top) and Yaw History (bottom) of Warmer #2

cycle of 3 degrees for the remainder of the flight. Figure 24 shows an expanded view of the first 10 seconds of the σ_N plot. Nutation, represented by the higher frequency cycles, and the precession represented by the lower frequency cycles can be more clearly seen in this plot.

Using a half muzzle brake, MRP #1 was fired with a muzzle velocity of 337 m/s. As depicted in the $\dot{\varphi}$, σ_N and expanded σ_N plots, Figs. 25 and 26, respectively, MRP #1 was unstable in flight. The half muzzle brake induced 5 degrees of yaw on the projectile at muzzle exit. Typical of a viscous fill type instability is the abrupt despin and rapid yaw growth. After approximately 7 seconds of flight the round became unstable. Flight time for the MRP #1 was 18 seconds, well under the 35 seconds for the stable Warmer #2. From the expanded σ_N plot (Fig. 26), it can be determined that the nutation or fast precession was the unstable mode.

MRP #2 was a repeat of MRP #1. Figures 27 and 28 present the $\dot{\varphi}$, σ_N and expanded σ_N plots. This round was also unstable, reproducing the results of MRP #1.

The final shot, MRP #3, was made without a muzzle brake on the gun tube which imparted only 2 degrees of yaw to the projectile at muzzle exit. Figures 29 and 30 present the $\dot{\varphi}$, σ_N and expanded σ_N plots, respectively. Even for the less severe launch case the round still became unstable, but took almost twice as long, 13 seconds, for the abrupt despin and corresponding yaw growth. Also, because of the longer time to become unstable, the flight time was slightly longer, 23 seconds, but still far short of the 35 second full range flight time of Warmer #1. The undamped nutation mode again was the reason for the yaw growth.

4.3.5 Flight Test Conclusions and Summary

In contradiction to the results of the spin fixture stability study of Phase 2, the Phase 3 flight test showed that a MRP with a four 500 ml Hespan IV bag payload would produce a liquid-filled flight instability. The induced yaw angles at the gun tube exit were well below the critical value of 10 degrees established by the spin fixture tests. After further analysis into possible reasons for the discrepancy, it was discovered that the longitudinal baffle plate might have been undersized and failed during launch. If this were the case, then the internal configuration of the flight payload canister that flew is not known and was not simulated on the spin fixture during Phase 2. Since these flight tests, a new baffle has been designed, and an additional MRP payload canister system has been fabricated. This MRP will be flight tested with a yawsonde during the next scheduled ARL flight test. This test will determine if a failed baffle could have caused the flight instability. As the results currently stand, the character of the yawsonde data lead to the conclusion that a dangerous payload-induced instability occurs when these MRPs are fired. The true nature of this instability can only be understood and corrected with a great deal of additional effort.

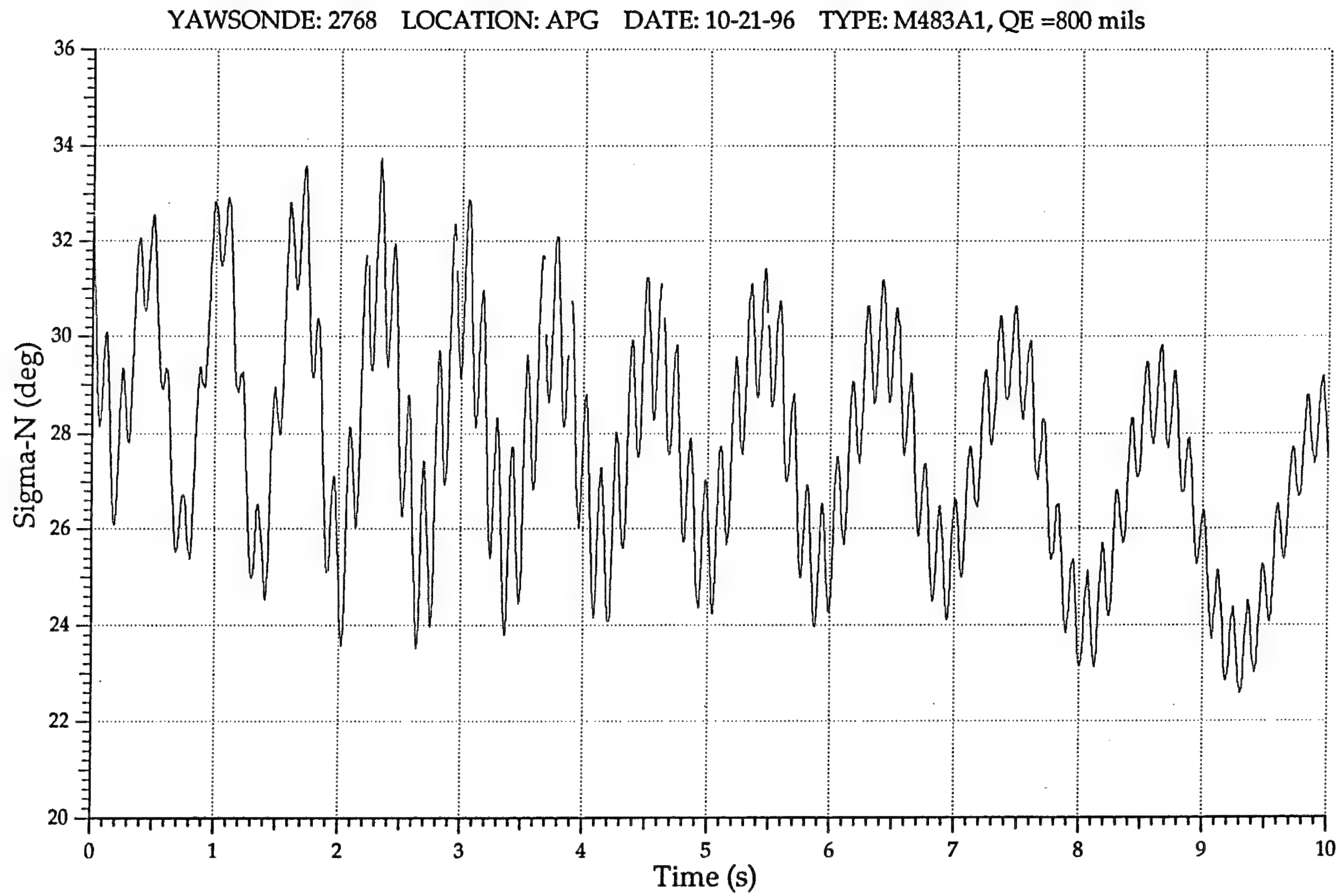
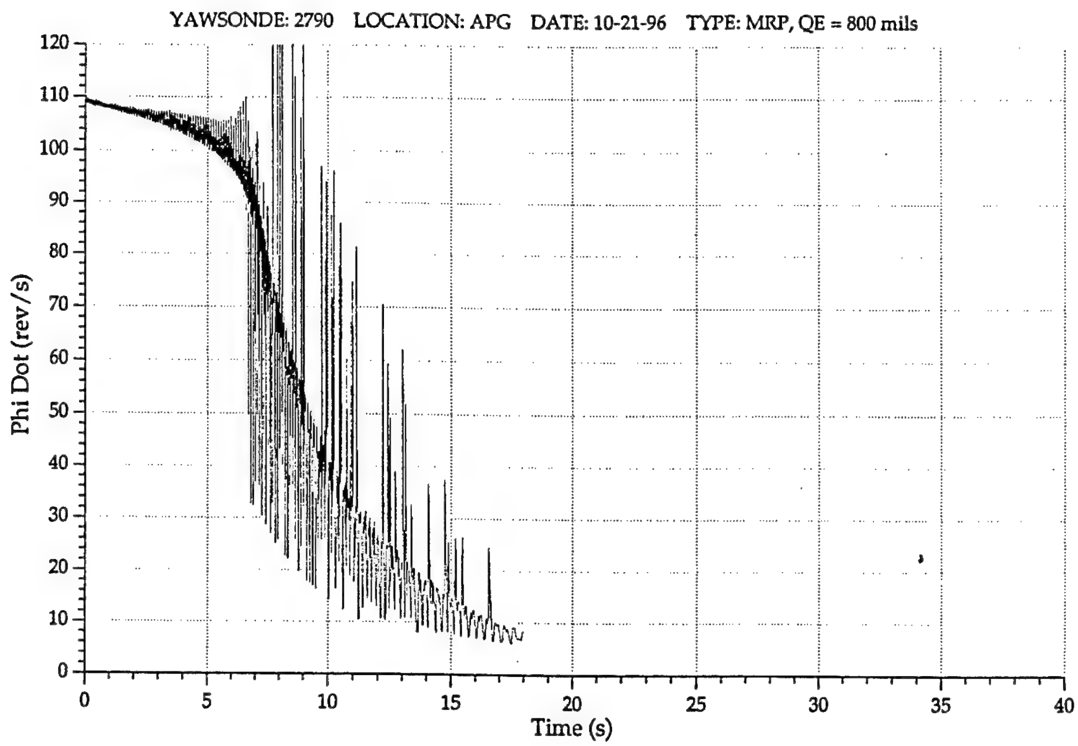


Figure 24: Expanded View of Yaw History for Warmer #2



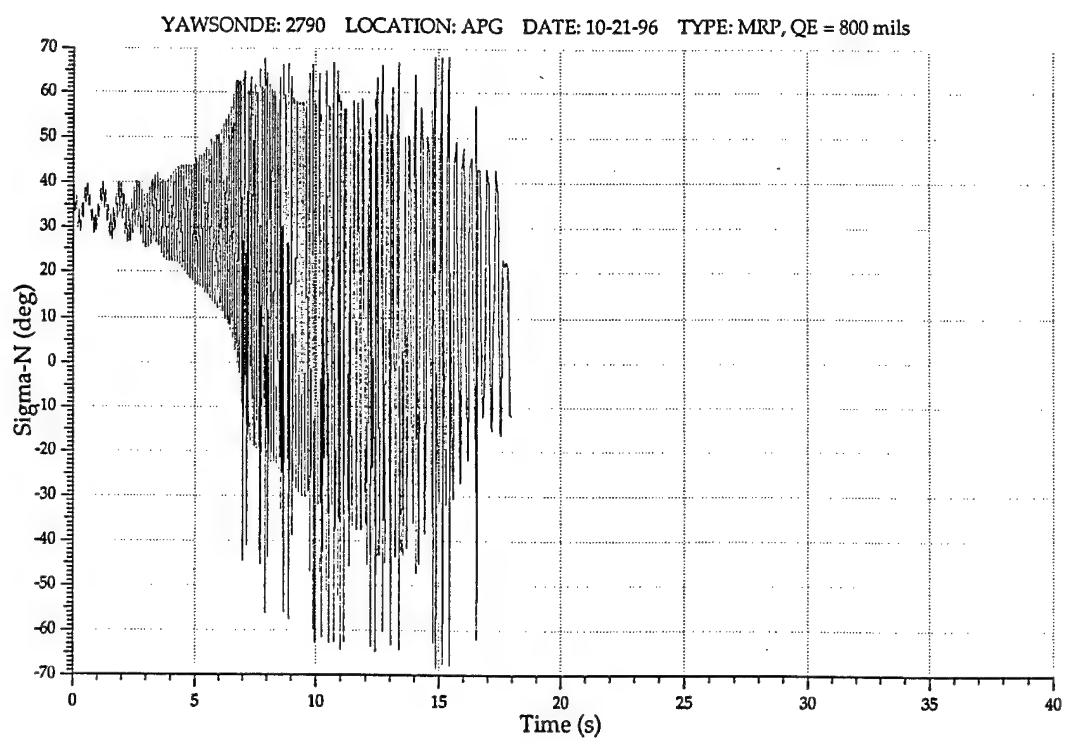


Figure 25: Spin Decay (top) and Yaw History (bottom) of MRP #1

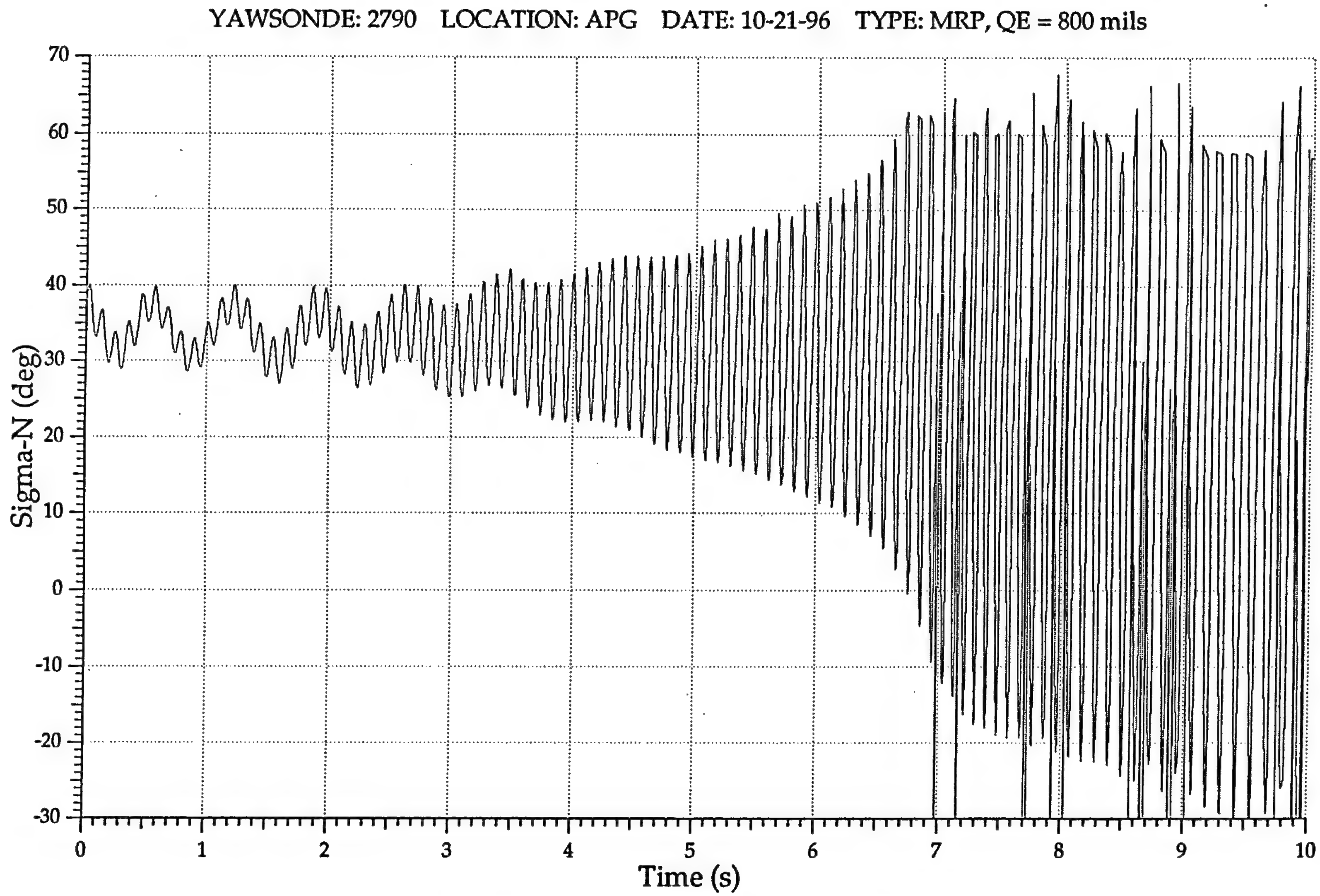
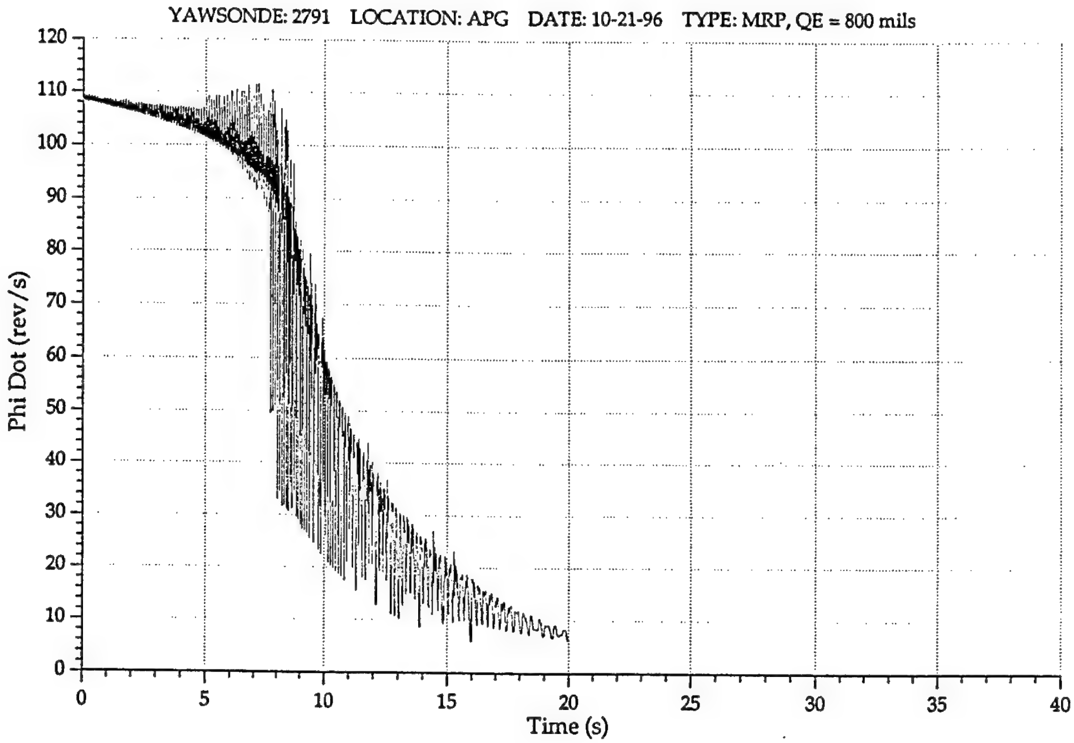


Figure 26: Expanded View of Yaw History for MRP #1



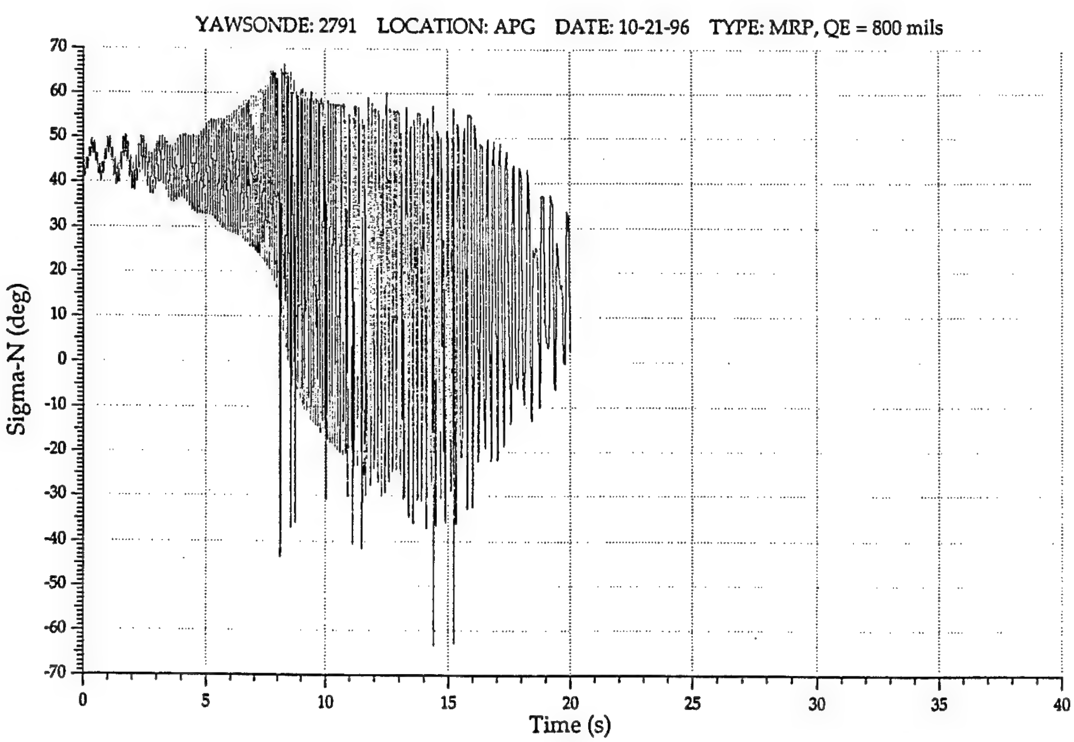


Figure 27: Spin Decay (top) and Yaw History (bottom) of MRP #2

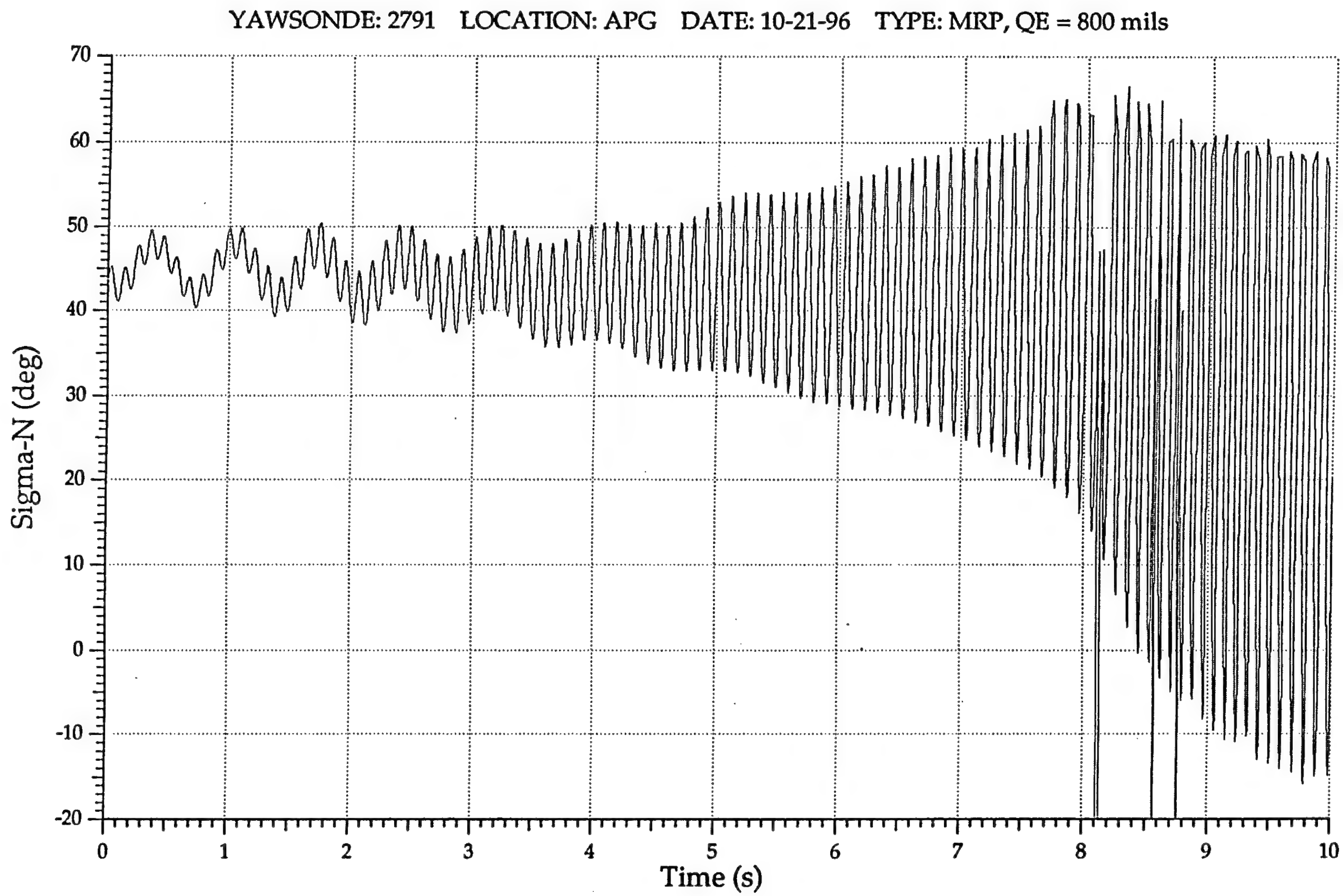
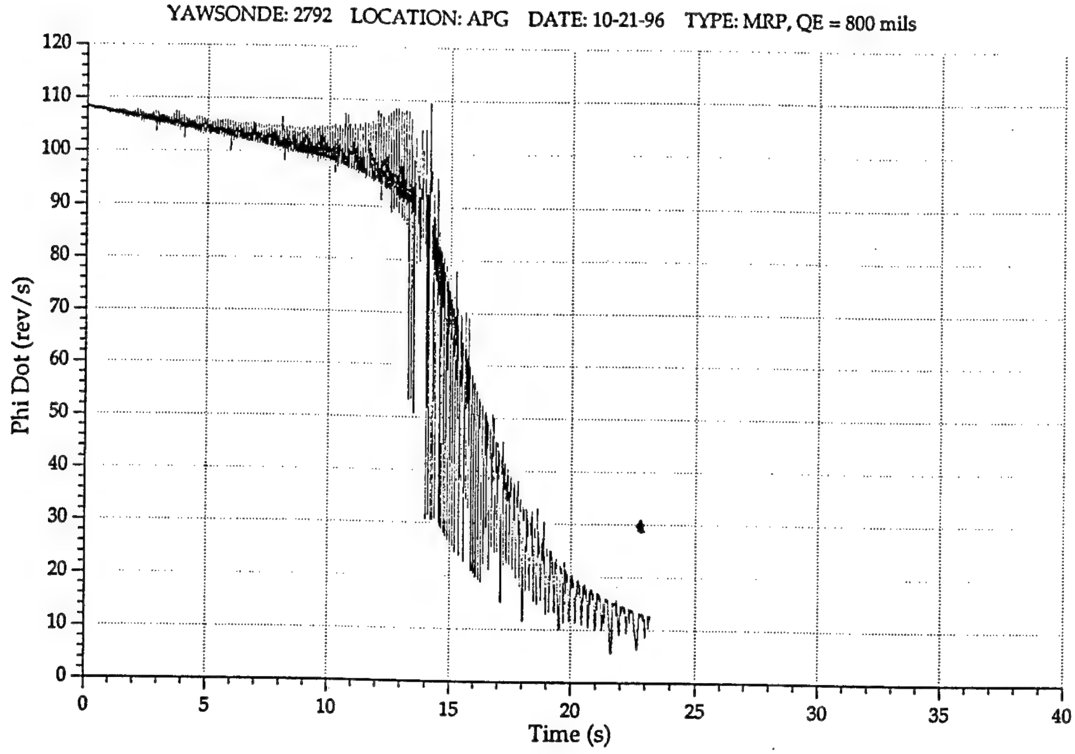


Figure 28: Expanded View of Yaw History for MRP #2



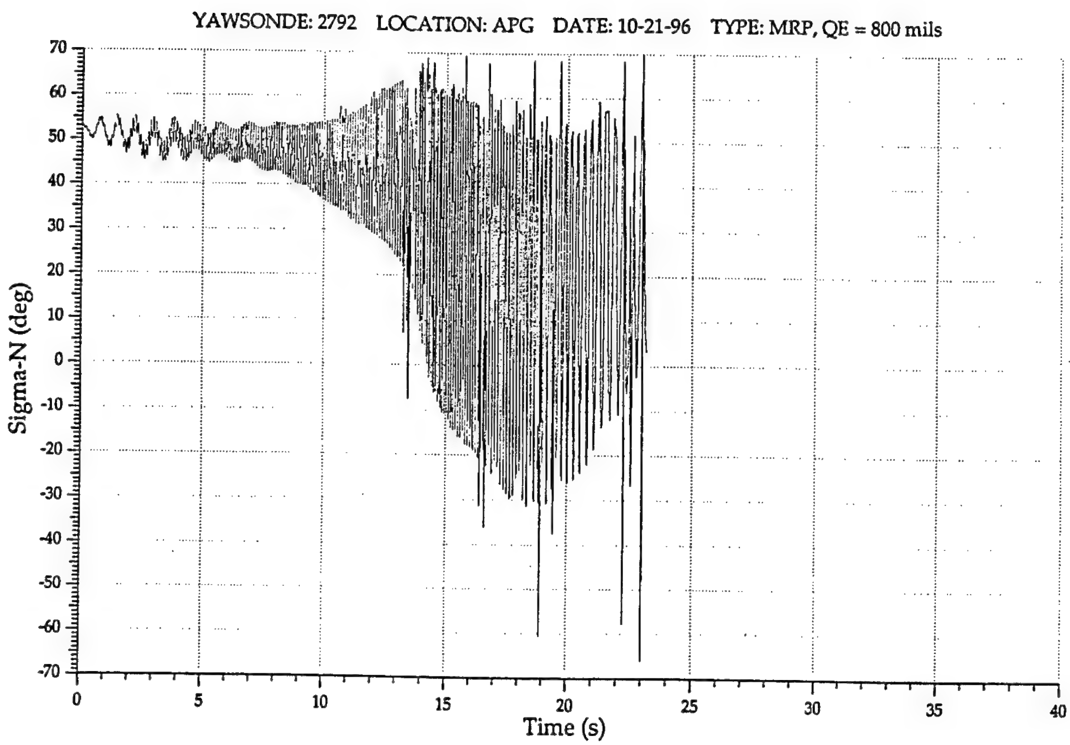


Figure 29: Spin Decay (top) and Yaw History (bottom) of MRP #3

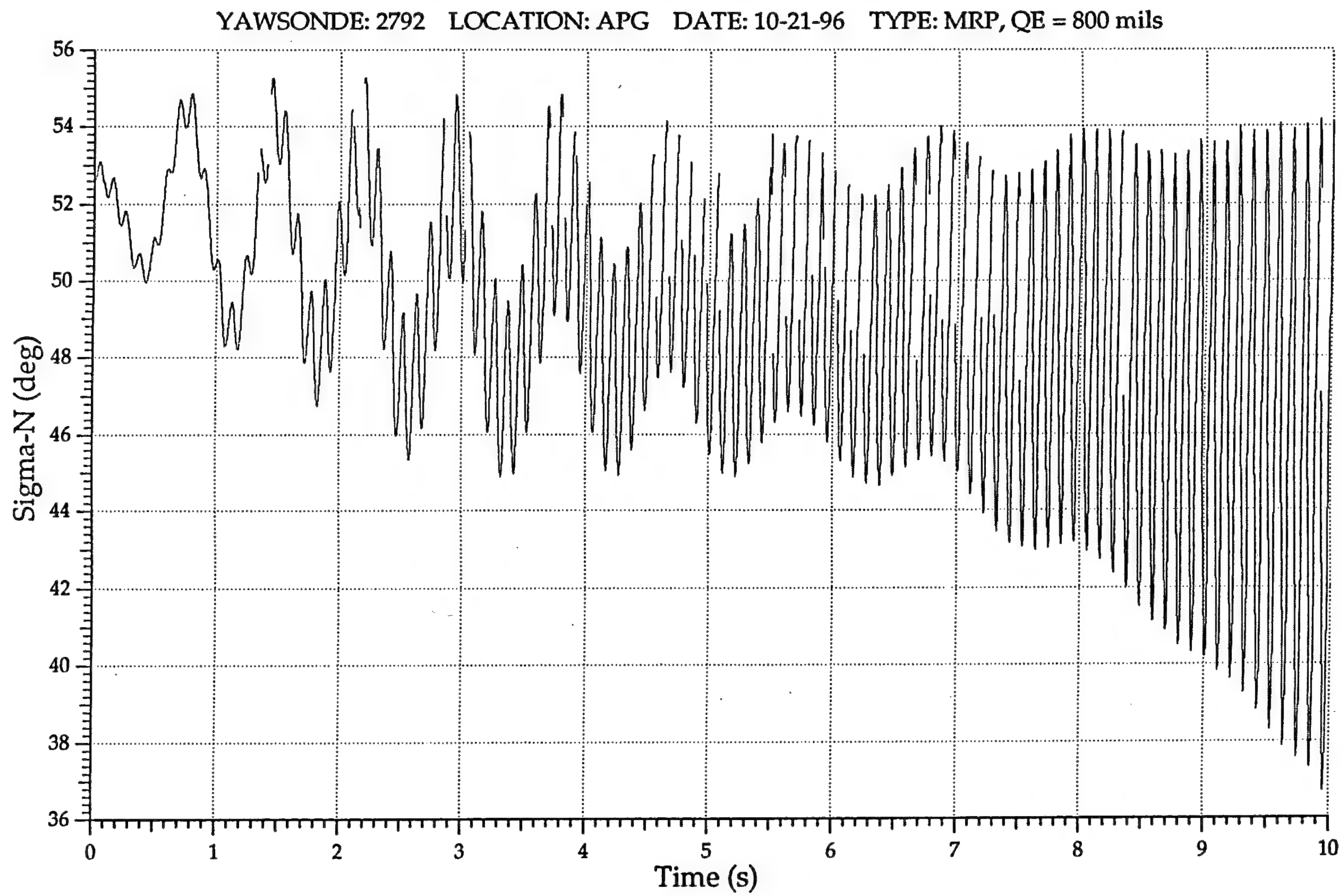


Figure 30: Expanded View of Yaw History for MRP #3

4.4 Feasibility Study Conclusion and Summary

From the Phase 1 shock fixture tests it was indicated that through appropriate packaging, standard off-the-shelf, 500 ml IV bags could survive 155mm artillery launch environments in excess of 10,000 g's. After several iterations between shock fixture testing and canister design, a two-piece canister geometry with internal baffle was selected.

The spin fixture tests of Phase 2 indicated that 500 ml Hespan bags were a better choice than Lactated Ringer's. Two different payload canister designs and several bag arrangements were tested. For coning angles above 10 degrees the bags began to show signs of wear and failure. Results also indicated that the baffles in the single canister design are a major contributor to the liquid induced despin moment.

The Phase 3 flight test results showed that a Hespan filled MRP developed a liquid induced flight instability even when launched under low yaw induced conditions. These results contradicted the Phase 2 findings. Solid filled slug projectiles which matched the physical properties of the MRP were shot to confirm that the lower weight of the MRP would not cause an aerodynamic instability. A possible baffle failure may be the cause of the discrepancy between the Phase 2 and 3 results and a future flight test is planned to retest the Hespan MRP with a strengthened baffle.

5. Recommendations and Future Work

Below is a prioritized list (highest to lowest) of recommended future work needed to identify and correct the MRP liquid payload induced flight instability.

1. Redesign the MRP payload canister to match the newly designed Bright Falcon system. Bright Falcon is a proposed program at Armament Research, Development and Engineering Center (ARDEC) to develop an intelligent artillery borne delivery system for accurately transporting various cargoes to ground targets. Bright Falcon replaces the Savage effort that focused on artillery delivered combat logistics. The MRP canisters developed for the Savage program used preliminary internal payload module dimensions because the design of the Savage payload module had not been finalized when the MRP study began. Since additional spin fixture, shock table, and flight tests will be required to identify the cause of the liquid induced flight instability, a more representative version of the final MRP canister should be used for these tests. Also, now that the payload module dimensions have been defined, the MRP canisters can be designed to take advantage of all available payload volume.

2. Conduct rheological studies of Hespan, Lactated Ringer's and any other MRP fluids of interest. These studies would help explain the observed, significant differences in spin fixture results between Hespan and Lactated Ringer's.

Also, the rheological information would quantify the different fluids with regard to their viscosities, densities, shear stresses, etc. and determine if they are Newtonian.

3. Conduct additional spin fixture, shock table, and flight tests to evaluate the redesigned MRP/Bright Falcon payload canister. The follow on spin fixture phase could include clear canister testing using high speed video to observe the relative motion of the IV bags with respect to the canister.

4. Based on the spin fixture results from this study that showed a substantial reduction in despin moment with the removal of the baffle, it is recommended that further spin fixture and shock table tests be conducted to determine if the baffle can be removed without compromising the IV bags.

5. A total redesign of the IV bags by manufactures to optimize packaging volume and bag strength would greatly benefit this program.

6. Investigate with both shock fixture and spin fixture tests to determine if the baffle could be removed from the two-canister system while retaining set-back survivability and low induced payload despin moment. Test would also be required to determine if the bags would be damaged during spinup without the support of a baffle.

It is highly recommended that any future flight tests employ some type of system to recover the rounds. The recovery and analyses of the payload canisters would greatly aid in the understanding of any flight stability problems.

Although the results from this study appear contradictory, and less than desirable, the basic premise supporting the Savage/Bright Falcon initiative remains an achievable and necessary goal. The need for a rapid and safe method of delivering life sustaining logistics, especially medical supplies, to combatant troops should remain a high priority. It is the opinion of the authors of this report, that with additional design and testing, the Savage/Bright Falcon system will provide a state-of-the-art method for critical resupply.

6. List of Symbols

P	hydrostatic pressure
ρ	fluid density
h	high of fluid
σ_N	solar aspect angel
$\dot{\phi}$	Eulerian roll angle

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Pointer, R. W., BG Ret. and Dean, C. E., MAJ, *Combat Logistics Program a Boom for Army Forces*, National Defense, October 1996, pp. 38-39.

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